

## LIQUID HYDROGEN MASS FLOWMETER EVALUATION

FACILITY FORM 502  
N65-18197  
(ACCESSION NUMBER)  
186  
(PAGE)  
CR-60990  
(NASA CR OR TMX OR AD NUMBER)

(THRU)  
1  
(CODE)  
14  
(CATEGORY)

CONTRACT NO. NAS8-1526

JANUARY 1965

FINAL REPORT

GPO PRICE \$ \_\_\_\_\_

OTS PRICE(S) \$ \_\_\_\_\_

Hard copy (HC) \$5.00

Microfiche (MF) \$1.00

**WYLE LABORATORIES**

EL SEGUNDO, CALIFORNIA

PREPARED FOR

GEORGE C. MARSHALL SPACE FLIGHT CENTER  
NATIONAL AERONAUTICS AND SPACE ADMINISTRATION

HUNTSVILLE, ALABAMA

# **LIQUID HYDROGEN MASS FLOWMETER EVALUATION**

CONTRACT NO. NAS8-1526

JANUARY 1965

FINAL REPORT

**WYLE LABORATORIES**

EL SEGUNDO, CALIFORNIA

PREPARED FOR

**GEORGE C. MARSHALL SPACE FLIGHT CENTER  
NATIONAL AERONAUTICS AND SPACE ADMINISTRATION**

HUNTSVILLE, ALABAMA



## PREFACE

Wyle Laboratories wishes to acknowledge the support and technical direction which has been provided by the Test Division of the George C. Marshall Space Flight Center and in particular the interest and creative imagination supplied to this program by Mr. A. E. Schuler and his staff.

The following personnel provided primary contributions to this program.

George C. Marshall Space Flight Center

A. E. Schuler  
L. Thompson  
C. Gibbs

Wyle Laboratories

L. N. Mortenson  
H. R. Wheelock  
F. Robinett

## TABLE OF CONTENTS

	<u>Page Number</u>
TITLE PAGE	i
PREFACE	ii
TABLE OF CONTENTS	iii
LIST OF FIGURES	iv
LIST OF TABLES	ix
ABSTRACT	xi
INTRODUCTORY SUMMARY	1
LITERATURE AND INDUSTRY SURVEY	7
DESIGN AND FABRICATION OF THE CALIBRATION SYSTEM	13
CALIBRATION SYSTEM ERROR ANALYSIS	31
EVALUATION OF THE DECKER CORPORATION GYROSCOPIC MASS FLOWMETER	41
EVALUATION OF THE POTTER AERONAUTICAL CORPORATION TWIN TURBINE MASS FLOWMETER	56
EVALUATION OF THE WAUGH ENGINEERING COMPANY AXIAL MOMENTUM MASS FLOWMETER	81
EVALUATION OF THE GENERAL ELECTRIC CORPORATION ANGULAR MOMENTUM MASS FLOWMETER	117
QUANTUM-DYNAMICS, COMPANY DENSITY COMPENSATING MASS FLOWMETER	138
BIBLIOGRAPHY	154

## LIST OF FIGURES

<u>FIGURE</u>		<u>Page Number</u>
1	Wyle Laboratories Norco Test Facility	14
2	Detail of the 650 Gallon Calibration Tank	19
3	Primary Components Situated on the Scale Platform	20
4	Photograph of the Test Chamber Retracted Exposing the Test Meter	21
5	Inner and Outer Shell of Calibration Tank prior to Application of Fiberglass and Cast Foam Insulation	22
6	Inner Vessel of Calibration Tank during Application of Fiberglass prior to Application of Cast Foam Insulation	23
7	Calibration System Control Console	26
8	Variable Density System Schematic	27
9	Helium Cooling Coils Removed from the Liquid Nitrogen Refrigerant	29
10	Helium Cooling Coils Soldered to the Liquid Hydrogen Piping Downstream of the Flowmeter	30
11	Graphical Representation of Errors Created by Dynamic Lag and Switch Repeatability	34
12	Photograph of the Calibration System Prover	38
13	Prover System Block Diagram	39
14	Decker Corporation Vibrating Gyroscopic Mass Flowmeter	42
15	Installation of Decker Flowmeter in Calibration System	43

LIST OF FIGURES  
(Cont.)

<u>FIGURE</u>		<u>Page Number</u>
16	Decker - Liquid Nitrogen Calibration	47
17	Decker - Liquid Nitrogen Calibration	48
18	Decker - Liquid Hydrogen Calibration	50
19	Decker - Liquid Hydrogen Calibration	51
20	Decker - Liquid Hydrogen Calibration	53
21	Decker - Liquid Hydrogen Calibration	54
22	Decker - Liquid Hydrogen Pressure Drop Characteristics	55
23	Potter Twin Turbine Mass Flowmeter	57
24	3-Inch Potter Twin Turbine Mass Flowmeter	58
25	Instrumentation Utilized during Calibration Potter Mass Flowmeter	60
26	Potter - Liquid Hydrogen Calibration	63
27	Potter - Liquid Hydrogen Calibration	65
28	Potter - Liquid Hydrogen Calibration	68
29	Potter - Liquid Hydrogen Calibration	69
30	Potter - Liquid Hydrogen Calibration	70
31	Potter - Liquid Hydrogen Pressure Drop Characteristics	71
32	Potter - Liquid Hydrogen Calibration	74
33	Potter - Liquid Hydrogen Calibration	75
34	Potter - Liquid Hydrogen Calibration	76

LIST OF FIGURES  
(Cont. )

<u>FIGURE</u>		<u>Page Number</u>
35	Potter - Liquid Hydrogen Pressure Drop Characteristics	77
36	Potter - Liquid Hydrogen, Gaseous Helium Dual Phase Calibration	79
37	Potter - Liquid Hydrogen, Gaseous Helium Dual Phase Calibration	80
38	Waugh Axial Momentum Mass Flowmeter	82
39	Annular Flow Passage and Anti-Swirl Grid in the Flowmeter Inlet	83
40	Tandem Calibration of Flowmeters Serial Numbers 16162 and 16164	84
41	Waugh - Liquid Hydrogen Calibration	92
42	Waugh - Liquid Hydrogen Calibration	93
43	Waugh - Liquid Hydrogen Calibration	96
44	Waugh - Liquid Hydrogen Calibration	97
45	Waugh - Liquid Hydrogen Calibration	100
46	Waugh - Liquid Hydrogen Calibration	101
47	Waugh - Liquid Hydrogen Calibration	105
48	Waugh - Liquid Hydrogen Calibration	112
49	Waugh - Liquid Hydrogen, Gaseous Helium Dual Phase Calibration	115
50	Waugh - Liquid Hydrogen Pressure Drop Characteristics	116

LIST OF FIGURES  
(Cont.)

<u>FIGURE</u>		<u>Page Number</u>
51	G. E. Mass Flowmeter - Model TJ-64	118
52	G. E. Mass Flowmeter - Model Z-809	120
53	G. E. Mass Flowmeter - Model TJ-64	122
54	G. E. - Liquid Hydrogen Calibration	126
55	G. E. - Liquid Hydrogen Calibration	129
56	G. E. - Liquid Hydrogen Calibration	130
57	G. E. - Liquid Hydrogen Pressure Drop Characteristics	131
58	G. E. - Liquid Hydrogen Calibration	133
59	G. E. - Liquid Hydrogen Calibration	134
60	G. E. - Liquid Hydrogen Pressure Drop Characteristics	135
61	G. E. - Liquid Hydrogen, Gaseous Helium Dual Phase Calibration	137
62	Quantum Dynamics - 3-Inch Mass Flowmeter	139
63	Quantum Dynamics Flowmeter Inlet, showing the Concentric Dielectric Sensing Elements.	140
64	Quantum Dynamics - Density Compensating Mass Flowmeter Instrumentation	141
65	Quantum Dynamics - Liquid Hydrogen Calibration	144
66	Quantum Dynamics - Liquid Hydrogen Calibration	148

LIST OF FIGURES  
(Cont.)

<u>FIGURE</u>		<u>Page Number</u>
67	Quantum Dynamics - Liquid Hydrogen Calibration	149
68	Quantum Dynamics - Liquid Hydrogen Calibration	150
69	Quantum Dynamics - Liquid Hydrogen Calibration	151
70	Quantum Dynamics - Liquid Hydrogen Calibration	152
71	Quantum Dynamics - Liquid Hydrogen Pressure Drop Characteristics	153

## LIST OF TABLES

<u>TABLE</u>		<u>Page Number</u>
1	Flowmeters Selected for Evaluation	2
2	Performance of Mass Flowmeters During Calibration with Liquid Hydrogen	4
2a	Comparison of Single-Phase and Two-Phase Performance	5
3	Summary of Cryogenic Mass Flowmeter Survey	8
4	Summary of Random and Systematic Errors	36
5	Test Results obtained with the Calibration System Sensitivity Prover	40
6	Decker - Liquid Nitrogen Calibration	46
7	Decker - Liquid Hydrogen Calibration	49
8	Decker - Liquid Hydrogen Calibration	52
9	Potter - Liquid Hydrogen Calibration	66
10	Potter - Liquid Hydrogen Calibration	73
11	Potter - Liquid Hydrogen, Gaseous Helium Dual Phase Calibrations	78
12	Waugh - Liquid Hydrogen Calibration	88
13	Waugh - Liquid Hydrogen Calibration	94
14	Waugh - Liquid Hydrogen Calibration	98
15	Waugh - Liquid Hydrogen Calibration	102
16	Waugh - Liquid Hydrogen Calibration	104



LIST OF TABLES  
(Cont)

<u>TABLE</u>		<u>Page Number</u>
17	Waugh - Liquid Hydrogen Calibration	106
18	Waugh - Liquid Hydrogen Calibration	108
19	Waugh - Liquid Hydrogen Calibration	110
20	Waugh - Liquid Hydrogen Calibration	111
21	Waugh - Liquid Hydrogen, Gaseous Helium Dual Phase Calibration	113
22	G. E. - Liquid Hydrogen Calibration	125
23	G. E. - Liquid Hydrogen Calibration	127
24	G. E. - Liquid Hydrogen Calibration	132
25	G. E. - Liquid Hydrogen, Gaseous Helium Dual Phase Calibration	136
26	Quantum Dynamics - Liquid Hydrogen Calibration	143
27	Quantum Dynamics - Liquid Hydrogen Calibration	147

## ABSTRACT

18197

In recent years a growing need has developed for the capability to accurately measure the flow of cryogenic fluids, with particular emphasis placed upon the measurement of liquid hydrogen mass flow. As a result of this emphasis, Wyle Laboratories conducted a development program for the National Aeronautics and Space Administration's Marshall Space Flight Center for evaluation of several types of liquid hydrogen mass flow measurement devices.

The results of the NASA supported development program are presented in detail, with a discussion of the program scope, flowmeters which were evaluated, methods of evaluation, and test results obtained. Several types of currently available flowmeters are discussed which are capable of providing mass flow measurement accuracies in the order of  $\pm 0.5\%$ . In addition, the development of a unique liquid hydrogen flowmeter calibration system capable of obtaining accuracies in the order of  $\pm 0.1\%$  is described.

AUTHOR

## INTRODUCTORY SUMMARY

### The Mass Flowmeter Development Program

In the latter part of 1961, a program was initiated by NASA/MSFC, "To Study and Develop the State-of-the-Art of Liquid Hydrogen Mass Flow Measurement Techniques". Since that time, Wyle Laboratories has conducted surveys, developed primary flowmeter calibration systems, and performed extensive development testing of several interesting types of mass flow measurement devices.

The original intent of the liquid hydrogen mass flowmeter development program may be briefly summarized as follows:

Conduct an industry and government agency survey to determine the state-of-the-art and availability of liquid hydrogen mass flowmeters as of February 1961. This survey was to be a continuation of the previously sponsored NASA mass flow measurement program reported in Reference 1, the Armour Research Foundation report entitled, "Study of Mass Flowmeters".

Determine, on the basis of the industry and government agency survey, the most prominent flow measurement techniques currently available, and obtain the assistance of the flowmeter industry to support the proposed program through the supply of small-scale prototype mass flowmeters to undergo evaluation with liquid hydrogen.

Develop a precision flowmeter calibration system, and perform steady-state, single-phase and two-phase calibration testing of the prototype meters.

Soon after the initiation of the program, it was determined that evaluation of small-scale (smaller than 1-inch line size) flowmeters would not provide realistic information amenable to scaling to the actual desired flow rate of 5 pounds per second of liquid hydrogen, nor were any prototype models readily available in these smaller line sizes. The program was subsequently modified to encompass the study of full-scale flowmeters for flow rates up to 5 pounds per second.

As a result of the industry survey, the following flowmeters were selected for evaluation:

TABLE 1  
FLOWMETERS SELECTED FOR EVALUATION

Decker Corporation  
Gyroscopic Mass Flowmeter

General Electric Company  
Angular Momentum Mass Flowmeter

General Electric Company  
Angular Momentum Mass Flowmeter  
(Bypass Principle)

Potter Aeronautical Corporation  
Twin Turbine Mass Flowmeter

Quantum Dynamics Corporation  
Density-Compensated Mass Flowmeter

Waugh Engineering Company  
Angular Momentum Mass Flowmeter

The methods which were selected for the comparative evaluation of the various flowmeter types consisted of steady-state, single-phase calibration with liquid hydrogen and steady-state, two-phase calibrations with liquid hydrogen and gaseous helium mixtures. The flowmeters were initially subjected to steady-state, single-phase calibrations encompassing the particular flowmeter's flow range. Following the steady-state, single-phase flow tests, the flowmeters were subjected to varying conditions of two-phase flow to determine their ability to accurately measure true mass flow under adverse conditions. The variable density tests were performed by injecting varying quantities of gaseous helium into the flow stream well upstream of the flowmeter. Gas-to-liquid ratios up to 14% by volume were produced and the corresponding effects upon the flowmeters performance observed.

## The Flowmeter Calibration System

In selecting the principle for developing the precision calibration system, a great deal of emphasis was placed upon Wyle Laboratories prior experience in the use of time-weight calibration systems, and the desirability of directly comparing the indicated total output of the various flowmeters with accurately known increments of test fluid weight. Based upon these criteria and experience, the time-weight calibration principle was selected for use in the design of the primary calibration system.

The calibration system consists of a 650-gallon calibration tank mounted on a mechanical scale system, and utilizes helium gas to provide the necessary pressure for transferring the liquid hydrogen. To eliminate the requirement for measuring the pressurization gas added to the system during the calibration test, the helium pressurization gas is carried on board the scale system.

Calibrated drop weights were selected, permitting the use of the scale system as a null balance device rather than as an absolute weight measurement device.

Liquid hydrogen is transferred from the scale system through a 3-inch, vacuum-jacketed flexible hose assembly, and subsequently into a fluid piping system containing the flowmeters to be calibrated. At the end of each calibration run, the liquid hydrogen is transferred by a backflowing from the recovery tank through the test line to refill the calibration tank.

## Summary of Results

All of the flowmeter types selected for calibration were subjected to extensive steady-state single-phase calibrations with liquid hydrogen.

As a result of preliminary testing, several of the flowmeters were modified by the manufacturer and subsequently subjected to additional steady-state single-phase calibrations. The results of these calibrations are presented in subsequent sections of this report. Direct comparison of flowmeter performance is extremely difficult since the flow range, flow rates, extent of physical modifications, and intended service vary from flowmeter to flowmeter, thus precluding the rating of each flowmeter type on a relative performance basis.

In general, the performance of each flowmeter type may be summarized as follows:

TABLE 2  
PERFORMANCE OF MASS FLOWMETERS DURING  
CALIBRATION WITH LIQUID HYDROGEN

<u>Flowmeter</u>	<u>Repeatability (%)</u>
Decker Corporation Vibrating Gyro Mass Flowmeter	<u>+0.9</u>
General Electric Company Angular Momentum Mass Flowmeter	<u>+0.5</u>
General Electric Company Angular Momentum Mass Flowmeter (Bypass principle)	<u>+1.0</u>
Potter Aeronautical Corporation Twin Turbine Mass Flowmeter	<u>+0.5</u> <u>+0.12*</u>
Quantum Dynamics Corporation Density-Compensated Turbine Flowmeter	<u>+0.5</u> <u>+0.1*</u>
Waugh Engineering Company Angular Momentum Mass Flowmeter	<u>+0.5</u>

\* Volumetric data

It should be noted that the performance indicated represents the best performance that each flowmeter exhibited, and that nearly every flowmeter type exhibited a poorer performance at various times during the evaluation program. The results should therefore be used as a guide to indicate the current status of "state-of-the-art" performance which each flowmeter type is capable of achieving. Such information as long term stability, long term repeatability, and operating life of the flowmeters, cannot be inferred from this data.

Following the steady-state single-phase evaluation of the various flow-meter types, the General Electric Company (Bypass), Potter Aeronautical Corporation and Waugh Engineering Company mass flowmeters were subjected to steady-state two-phase flow conditions to evaluate the flowmeters performance during adverse flow conditions. In general, each flowmeter was subjected to two-phase flow conditions with gas to liquid ratios up to approximately 14%. The effect of the two-phase flow conditions upon the flow measurement accuracies of each flowmeter is summarized in the following table.

TABLE 2a  
COMPARISON OF SINGLE-PHASE AND  
TWO-PHASE PERFORMANCE

	<u>Single-Phase Repeatability (%)</u>	<u>Two-Phase Repeatability (%)</u>
General Electric Company Angular Momentum Mass Flowmeter (Bypass)	<u>+1.0</u>	<u>+1.0</u>
Potter Aeronautical Corporation Twin Turbine Mass Flowmeter	<u>+0.5</u>	<u>+2.0</u>
Waugh Engineering Company Angular Momentum Mass Flowmeter	<u>+0.5</u>	<u>+1.0</u>

It should be noted that the two-phase flow conditions did not produce a definable shift in calibration data which could be attributed to the two-phase flow, but resulted only in an increase in data scatter about the general single-phase calibration curve.

## Conclusions

The general conclusions which may be drawn from the performance of the NASA/MSFC sponsored program under Contract NAS8-1526 may be summarized as follows:

Several mass flowmeter types are currently in a sufficient state of hardware development to provide liquid hydrogen mass flow measurement accuracies under single-phase flow conditions on the order of  $\pm 0.5\%$ .

The performance of the mass flowmeter types which were evaluated show minor degradation in performance during two-phase flow conditions.

Additional investigation and development of flowmeter hardware are required to establish the long term accuracies, repeatability, and operating life of the flowmeter types which were investigated.



## LITERATURE AND INDUSTRY SURVEY

The survey phase of the program was conducted utilizing the Armour Research Report "Study of Mass Flowmeters" ARF Project D-173, Contract DA-11-022-ORD-2857 as the preliminary basis for contacting manufacturers and developers of mass flowmeters. In conjunction with the industry survey, the program objectives and philosophy were discussed with each manufacturer and/or government agency contacted as outlined below:

- a) Program requirements for flowmeter performance.
- b) Principle of flowmeter operation.
- c) Potential problem areas in the use of the flowmeter in a liquid hydrogen mass flow measurement application.
- d) Possible willingness of the manufacturer to participate in the evaluation phase of the program (submittal of meter on a loan basis and subsequent active participation in the data analysis and possible design improvement phases).
- e) Experience in either the field of mass flow measurement or the field of cryogenic flow measurement.
- f) Possible sources of additional technical information.

The results of the Literature and Industry Survey are summarized in the following table:

TABLE 3  
SUMMARY OF CRYOGENIC MASS FLOWMETER SURVEY  
 (As of February 1961)

<u>Organizations Contacted</u>	<u>Type of Instrument</u>
The Bendix Corporation Pioneer Central Division	Angular momentum, Single turbine driven at constant speed through a linear spring. Time period between driving motor and coupled turbine proportional to mass flow.
Consolidated Electrodynamics Corporation	Heat transfer (boundary layer).
Cox Division George L. Nankervis Company	Turbine volume meter with density compensation.
Daniel Orifice Fitting Company	Head meter with velocity compensation.
The Decker Corporation	Gyroscopic principle.
Fischer & Porter Company	Turbine volume meter with flow momentum drag body.
Flow Measurement Corporation	Heat transfer (boundary layer) Two basic types: a) Constant heat input; temperature rise related to mass flow. b) Constant temperature rise; heat input related to mass flow.

TABLE III (Cont.)  
SUMMARY OF CRYOGENIC MASS FLOWMETER SURVEY  
 (As of February 1961)

<u>Organizations Contacted</u>	<u>Type of Instrument</u>
Francisco Engineering Company, Inc.	Turbine volume meter with density compensation.
General Electric Company	Angular momentum. Turbine driven at constant speed imparts angular momentum to fluid which is removed in a second turbine. Resultant torque on second turbine is proportional to mass flow rate.
Gulton Industries, Inc.	Acoustic Volume meter with density compensation.
W. L. Maxson Company	Acoustic Volume meter with density compensation.
Millrich Engineering Company	Head meter with variable contoured orifice. Orifice area controlled by fluid density.
Potter Aeronautical Corporation	Twin turbine with linear spring coupling. Phase angle between turbines proportional to flow momentum with time period between rotating turbines proportional to mass flow.
Quantum-Dynamics Company	Turbine volume meter with density compensation.
Revere Corporation of America	Turbine volume meter with density compensation.
Space Instrumentation Corporation	Twin turbine type with servo drive.

TABLE 31 (Cont.)  
SUMMARY OF CRYOGENIC MASS FLOWMETER SURVEY  
 (As of February 1961)

<u>Organizations Contacted</u>	<u>Type of Instrument</u>
Standard Controls, Inc.	Drag on flexible reed. Flow momentum instrument with limited density compensation due to variable area.
Waugh Engineering Company	Angular momentum. Single. turbine driven with constant torque motor, turbine speed inversely proportional to mass flow.

## Selection of Flowmeters for Evaluation

In reviewing the current "state-of-the-art" of the flowmeter industry and in attempting to select the most promising cryogenic mass flow-meter design for subsequent evaluation in the experimental portion of the program, several restraints were established:

- 1) Emphasis was placed upon the evaluation of true mass flow-meters rather than inferential type instruments combining various volume and density signals external to the meter for the prediction of mass flow rate.
- 2) The program goals for the development of a mass flowmeter principle were tentatively established as:
  - a. Capable of measuring either single or two phase flow
  - b. Flow range: 0.5 to 5 pounds per second of liquid hydrogen
  - c. Accuracy: better than  $\pm 0.5\%$
- 3) For the current program, evaluation and development of meter designs was limited to reasonably well developed instruments. Additional restraints were initially imposed which required that the instrument manufacturer be willing to submit a flowmeter on a loan basis for evaluation and participate in the data analysis and possible design improvement phases.
- 4) The selection was further limited to meter designs with some existing experimental data substantiating a reasonable expectation of attaining an accuracy of  $\pm 0.5\%$ .

Within the confines of the above restrictions, the following meter manufacturers were selected to participate in the program:

The Decker Corporation	45 Monument Road Bola-Cynwyd, Pennsylvania
The Potter Aeronautical Corporation	U. S. Highway 22 Union, New Jersey

The Waugh Engineering Company  
(The Foxboro Co., Van Nuys Division)

7740 Lemona Avenue  
Van Nuys, California

The General Electric Corporation

Measurement Laboratory  
40 Federal Street  
West Lynn, Massachusetts

The Quantum-Dynamics, Co.

19458 Ventura Boulevard  
Tarzana, California

## DESIGN AND FABRICATION OF THE CALIBRATION SYSTEM

### Introduction

The experimental portion of the flowmeter development program was conducted at the Wyle Laboratories Norco Test Facility. The Norco Facility consists of approximately 500 acres developed for the performance of hazardous tests with liquid oxygen, liquid hydrogen, storable propellants and solid propellants. Figure 1 depicts the general location of each test complex.

The liquid hydrogen facility consists of a 13,000 gallon vacuum-jacketed hydrogen storage vessel, approximately 1700 sq. ft. of enclosed test area, 2400 sq. ft. of open test area, and approximately 1600 sq. ft. of office, shop, and control rooms.

### Discussion of Calibration Techniques

In designing a flowmeter calibration system, two fundamental techniques are available; the time-volume technique and the time-weight technique. It is perhaps noteworthy at this time to briefly summarize the relative advantages and disadvantages of the two calibration techniques.

The time-volume technique is based upon either the continuous or discrete measurement of volume versus time. In general, the discrete method is considered capable of providing better accuracy than the continuous techniques, and as such, the subsequent discussions will be limited to discrete level measurement.

Discrete volume measurements are usually made using point level sensors. Level sensors are installed in the calibration tank and the volume between the level sensors is precisely determined. An initial volume,  $V_1$ , is usually provided prior to the actuation of the upper level switch,  $S_1$ . This initial volume provides for the establishment of stable flow prior to the actuation of the first switch. The flow rate during the expulsion of the calibrated volume between the upper and lower switches is maintained constant, and as the liquid level reaches the lower level switch,  $S_2$ , a second timing pulse is generated. The totalizing flowmeter output signal during the time period between level switch actuations  $S_1$  and  $S_2$  is then compared with the volume between the level switches  $S_1$  and  $S_2$ . The flow rate is obtained by dividing the total volume between switch  $S_1$  and  $S_2$  by the elapsed time between switch actuations.

WYLE LABORATORIES NORCO TEST FACILITY

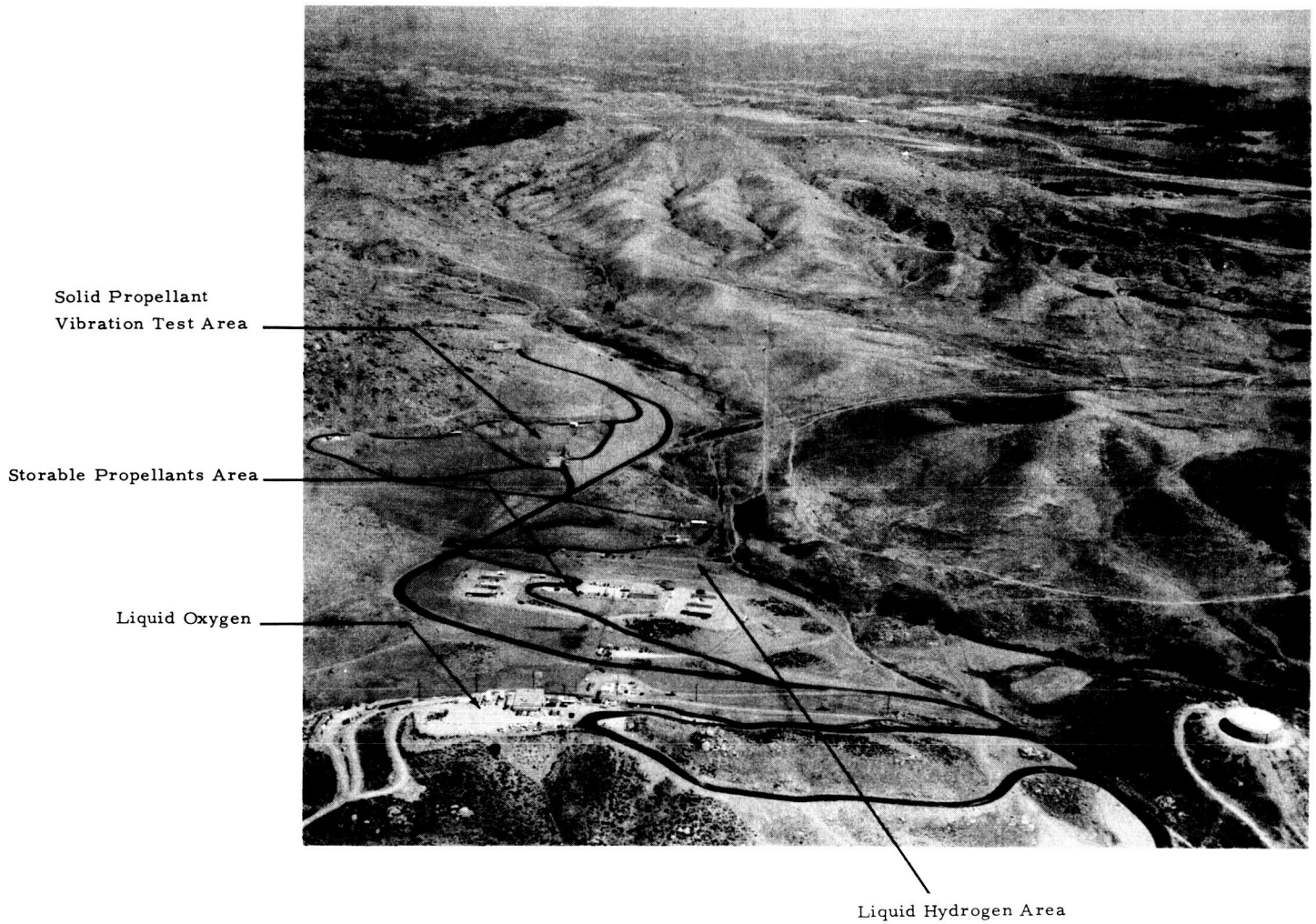


FIGURE 1



Pertinent aspects of the time-volume calibration system may be briefly summarized as follows:

- 1) Requires the use of a specially designed tank to optimize height versus volume conditions.
- 2) Ideally suited for the calibration of volume flowmeters since the volume between switch  $S_1$  and  $S_2$  is compared with the totalized volume signal obtained directly from the flowmeter being calibrated.
- 3) Requires a density conversion for the calibration of a mass flowmeter.
- 4) Requires prudent selection of level switches and design of the level switch installation.
- 5) Obtaining the correct volume between switch  $S_1$  and  $S_2$  for use in cryogenic application may be difficult since the volume, as calibrated with water, must then be corrected using analytical techniques to obtain the contracted volume at cryogenic conditions. An alternate approach for calibrating the volume between switch  $S_1$  and  $S_2$  is to weigh the tank plus contents with the actual cryogenic fluid in the tank. The weight change between switches  $S_1$  and  $S_2$  is then converted to the volume of cryogenic fluid using the temperature density characteristics of the fluid.
- 6) The volumetric system is unaffected by extraneous environments such as wind, hose connections, etc.
- 7) As noted in Reference 2, the calibration of cryogenic flowmeters must be conducted in a closed system to properly account for possible boil-off losses. The time-volume technique may be adapted to either closed system or open system operation.

The time-weight technique is based upon either the continuous or discrete measurement of weight change versus time. Weight measurements are usually made using either strain gauge techniques or beam balance-type scales. In general, the discrete method is considered capable of providing better accuracy than the continuous techniques, and as such, the subsequent discussions will be limited to discrete methods.

In the discrete weight change method, an initial weight of fluid is usually provided prior to the initial balance point  $B_1$ . This initial weight is provided for the establishment of stable flow, prior to the initial balance condition. The flow rate during the expulsion of the calibrated weight between the initial and final balance conditions is maintained constant. The weight of fluid during the calibration period between beam balance conditions  $B_1$  and  $B_2$  may be simulated by either the removal of counter poise weights from the balance arm, or the actual addition of a calibrated weight to the scale platform. As the second balance position is approached, a final timing pulse is generated. The totalized flowmeter output signal during the time period between initial and final scale balance positions  $B_1$  and  $B_2$  is then compared with the weight of fluid expelled from the calibration tank during the calibration period. In the calibration of volume type instruments, the basic weight change of the scale must be converted to a corresponding volume, by means of the temperature-density characteristics of the calibration fluid.

Pertinent aspects of the time-weight calibration system may be briefly summarized as follows:

- 1) Requires the use of specially designed lightweight tank configurations, or special techniques in the weighing system to eliminate a large system deadweight.
- 2) Ideally suited for the calibration of mass flowmeters, since the weight change between scale balance points  $B_1$  and  $B_2$  is compared with the totalized mass signal obtained directly from the flowmeter being calibrated.
- 3) Requires a density conversion for calibration of volume flowmeters.
- 4) Requires prudent selection of the weighing system and its installation.
- 5) The calibration tank pressurization medium added to the weighing system during the calibration period must be metered.

- 6) The system installation must be carefully designed to eliminate or minimize extraneous loading of the weighing system; i. e., side thrust loading, wind loading, piping connections, etc.
- 7) As noted in Reference 2, the calibration of cryogenic flowmeters must be conducted in a closed system to properly account for possible boil-off losses. The time-weight techniques can be adapted to either closed system or open system operation.

### The Calibration System

The time-weight calibration technique was selected for this program. This selection was based primarily on previous experience of Wyle with the design and operation of time-weight calibration systems, and the distinct advantage of obtaining a basic weight measurement in the calibration of mass flowmeters; thus eliminating the necessity of highly precise temperature measurements and subsequent density conversions.

The calibration system consists of a 650-gallon calibration tank and high pressure helium storage bottles mounted on a beam balance platform scale, as shown in Figures 2 and 3. The helium gas utilized to pressurize the calibration tank, is contained on the scale platform to eliminate the necessity of metering the pressurization gas during a calibration run. Connecting lines between the on-scale and off-scale portions of the system have been held to an absolute minimum. The largest connection between the scale system and ground reference is a 3-inch vacuum-jacketed flex hose through which the fluid is withdrawn from the calibration tank.

As indicated in Figure 3, fluid leaving the scale system enters a vacuum-jacketed transfer system, subsequently being returned to the 13,000 gallon recovery vessel. The transfer system was designed to include a removable vacuum shell which can be retracted, exposing a section of line approximately eight feet long. The technique of utilizing a removable vacuum shell facilitates the installation of the flowmeter undergoing calibration and its associated instrumentation.

Figure 4 shows the test chamber retracted during the installation of a test flowmeter.

The 650-gallon calibration tank incorporates the use of an unique method of foamed-in-place insulation. The concept of tank insulation is one in which the inner stainless steel vessel is wrapped with a two inch thick glass-matt prior to casting the foam insulation. The mold for the foam insulation is also the permanent outer shell of the completed tank assembly. The outer shell design is such that it may be completely sealed and rendered impervious to vapor transmission. The concepts of using a collapsible spacer material between the plastic foam and the inner tank and the vapor-tight outer shell have proven to be quite promising in the attainment of a light economic storage vessel which may be used for long term applications, without the normally attendant problems of cracking, deterioration of the plastic foam due to atmospheric conditions and water vapor diffusion into the foam. This tank has been in operation for over three years, and no evidence of deterioration of the insulation has become evident. The tank and shell are shown before assembly in Figures 5 and 6.

In addition to the basic gravimetric design, provisions were incorporated into the design of the calibration tank for the installation of liquid level sensors; thus allowing for the possibility of utilizing time-volume calibration techniques to substantiate the time-weight calibration data. In support of this effort, the tank was designed with an additional 6-inch access port, and has been calibrated several times with water.

FIGURE 2

DETAIL OF THE 650 GALLON CALIBRATION TANK

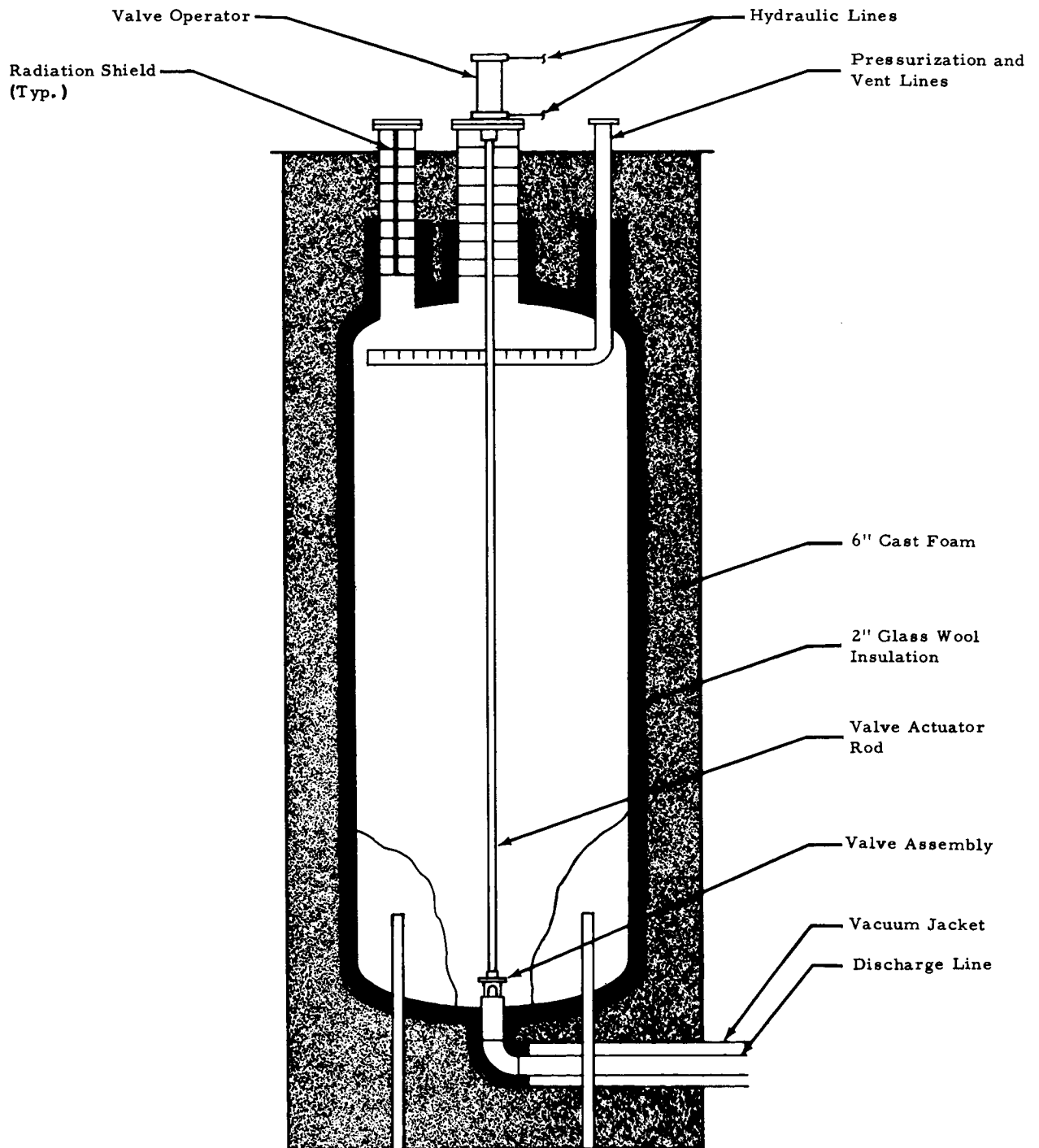
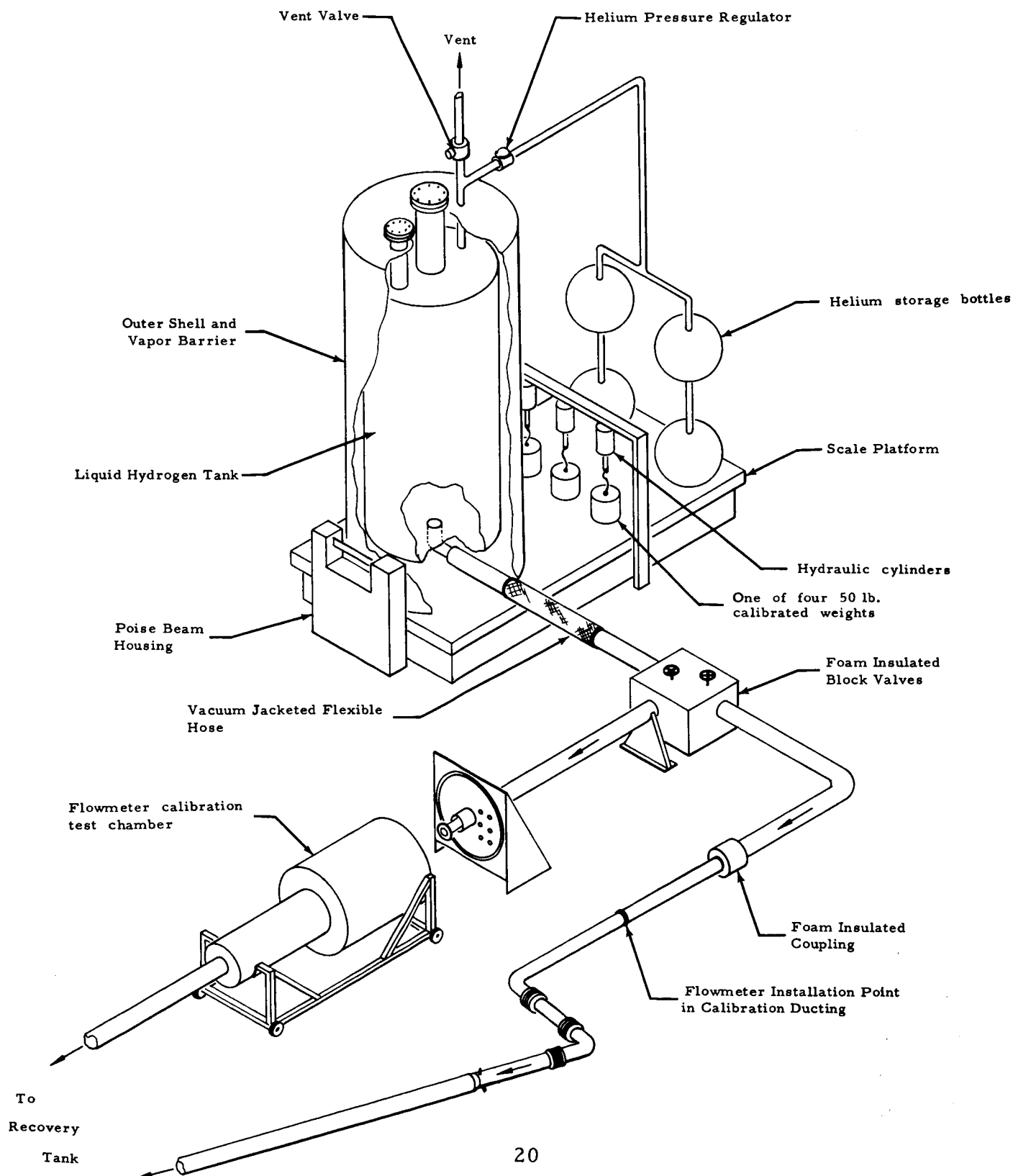
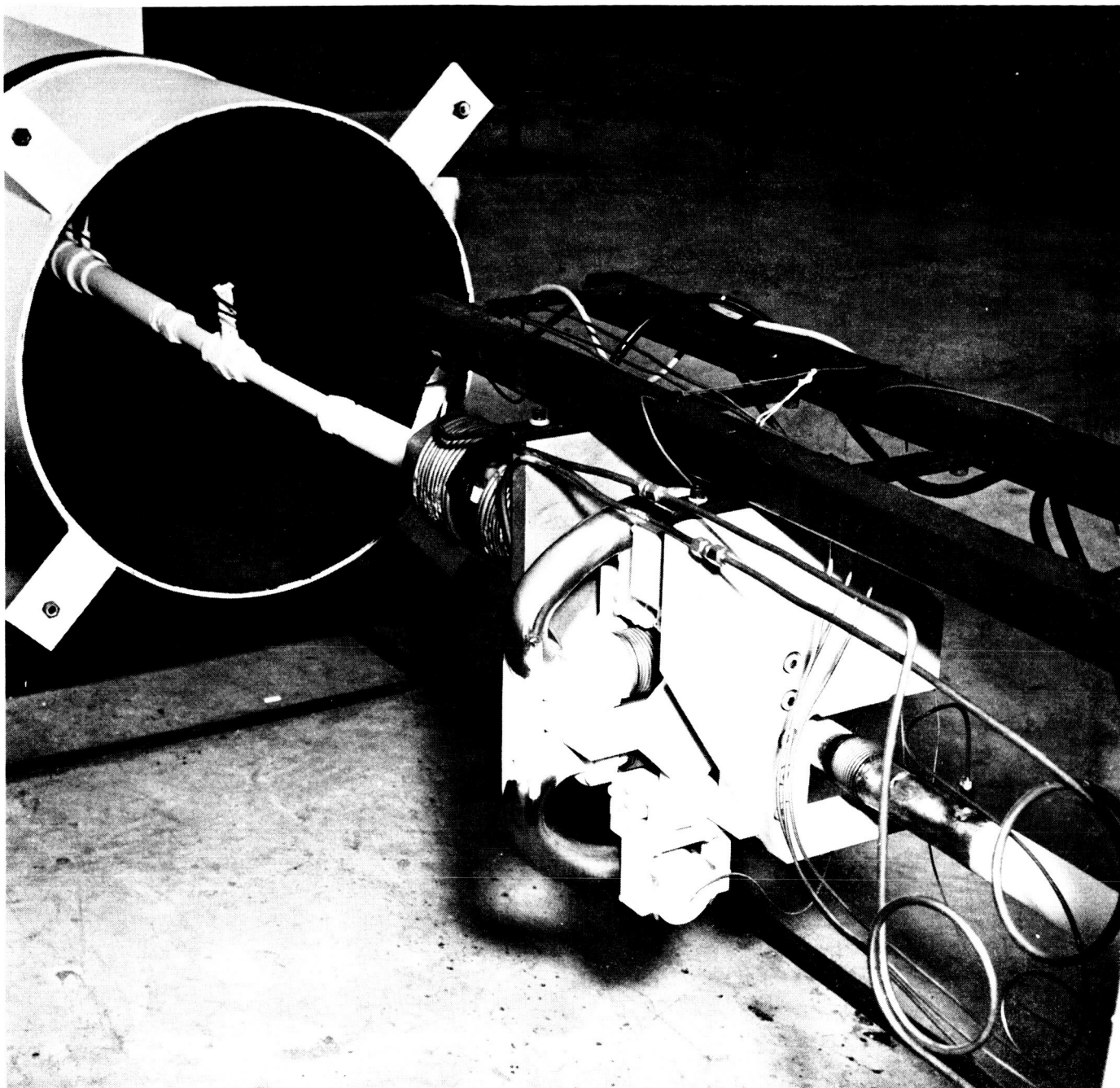


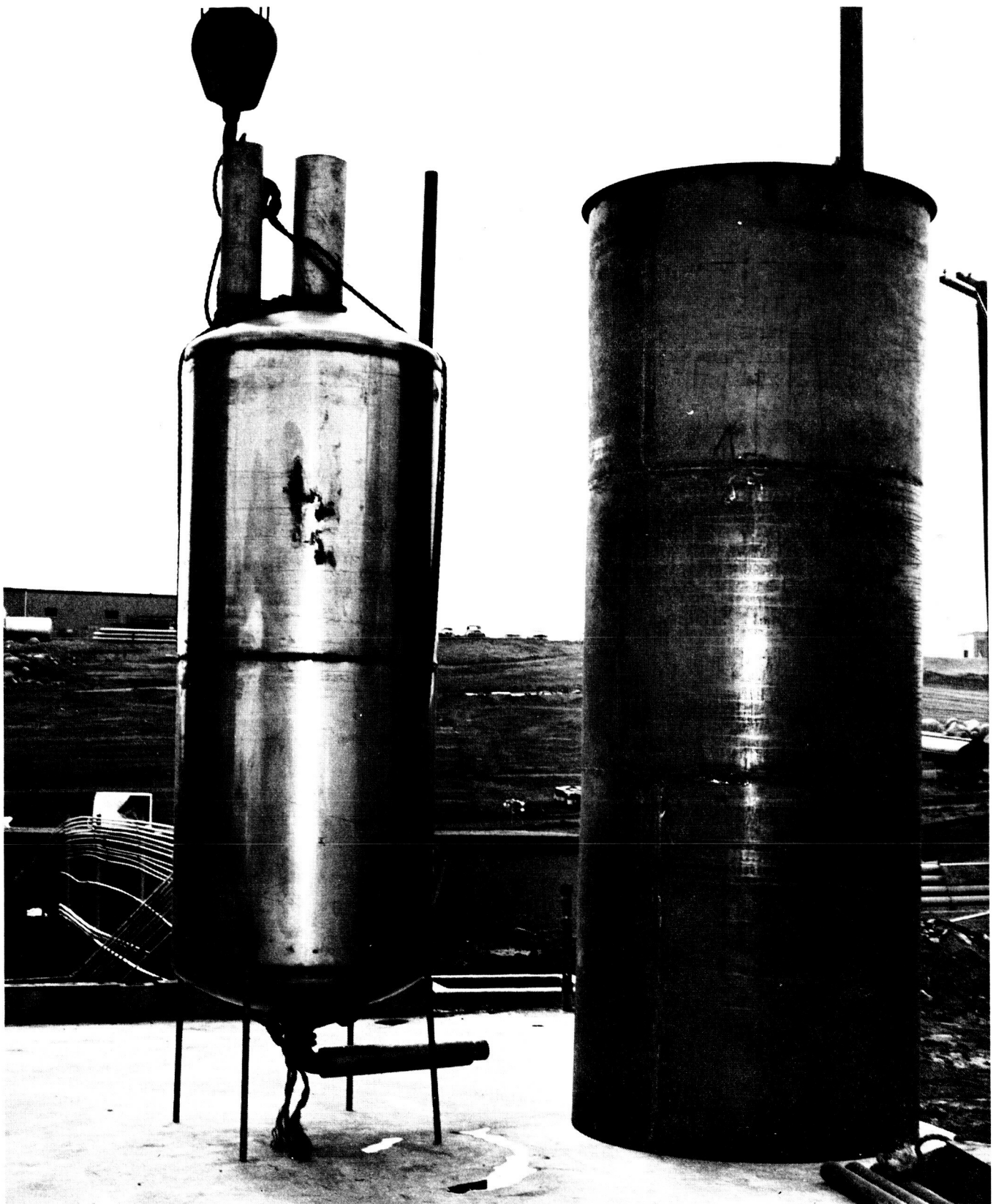
FIGURE 3  
PRIMARY COMPONENTS SITUATED ON THE SCALE PLATFORM





TEST CHAMBER RETRACTED EXPOSING THE TEST METER

FIGURE 4



INNER AND OUTER SHELL ASSEMBLIES OF CALIBRATION TANK PRIOR TO  
APPLICATION OF FIBERGLASS AND CAST FOAM INSULATION

FIGURE 5





INNER VESSEL OF CALIBRATION TANK DURING APPLICATION OF FIBERGLASS  
PRIOR TO APPLICATION OF CAST FOAM INSULATION

FIGURE 6

## Calibration Procedure

The calibration of a flowmeter is performed in a point-to-point manner; i. e., to obtain a single calibration point, one complete test run is required, since the totalized output of the flowmeter is compared with the total weight change on the scale system. Following the installation of the flowmeter in the test section, a typical test run is conducted in the following manner:

The test fluid is allowed to backflow through the flowmeter into the vented calibration tank. During this filling operation, the test fluid is allowed to stabilize at atmospheric pressure. Simultaneously, the helium pressurization system mounted on the scale platform is pressurized to approximately 1,800 psig in preparation for the test run. When the calibration tank is filled, the backflow of test fluid is discontinued. The vent valve on the 650-gallon calibration tank is closed and the tank pressure increased to approximately 50 psig using the scale mounted pressurization system. The predetermined flow rate is then rapidly established and steady state flow conditions are attained within approximately 8 to 12 seconds. At this point, the scale system which has been previously balanced to equal the initial weight of the full storage vessel, minus a weight of predetermined liquid, approaches the first null or balance condition of the scale. As the poise beam moves through its initial trig loop the capacitance switch which senses the beam movement is actuated initiating the following operations:

- a. A synchronous clock is started furnishing a time base for the calibration run.
- b. Specific instrumentation is activated to record both the instantaneous and totalized output of the flowmeter during the test period.
- c. Calibrated weights are lowered onto the scale platform corresponding to the weight of fluid to be removed from the scale system during the calibration period.

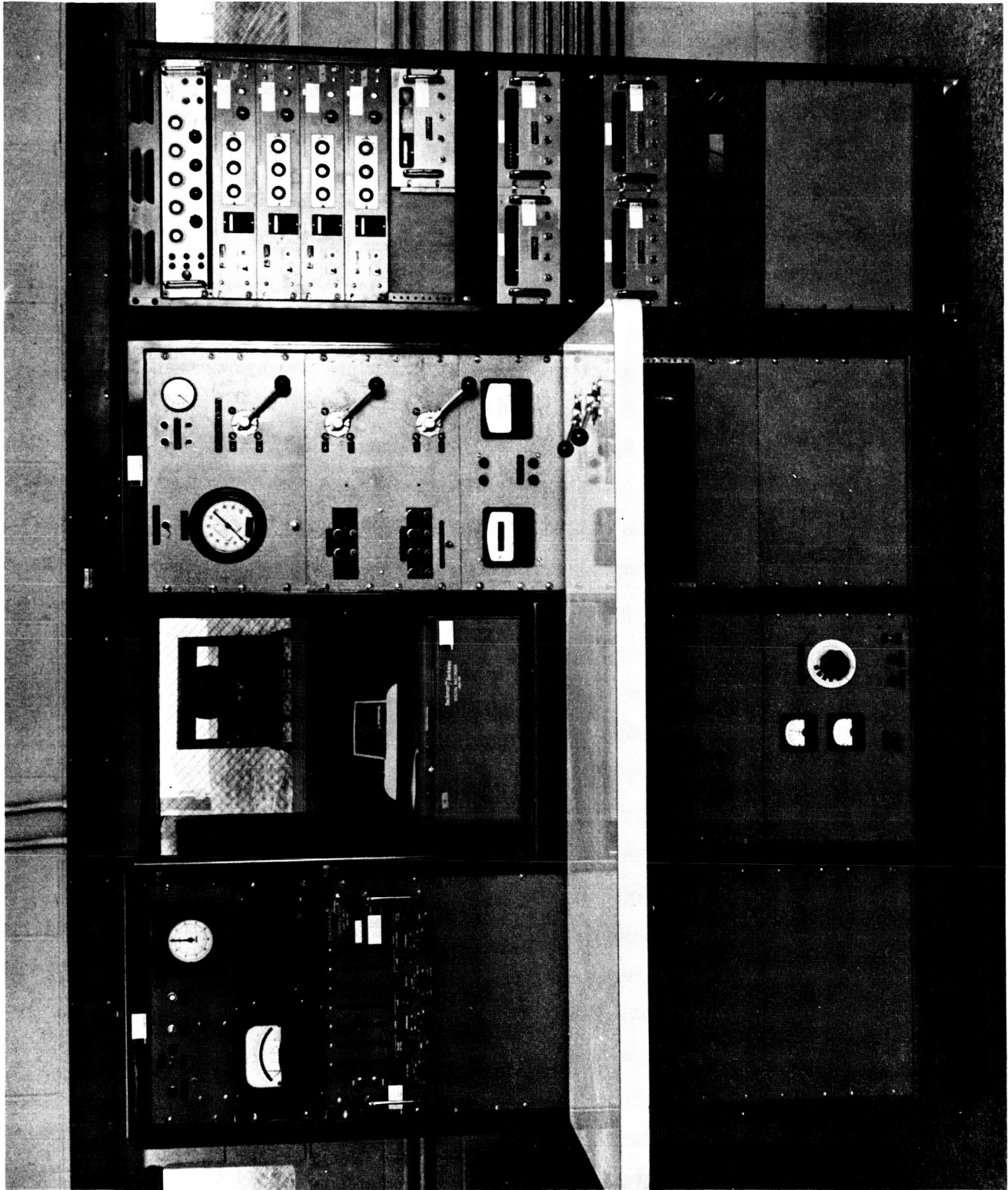
The addition of the calibrated weights to the scale platform causes the scale to become unbalanced and the balance beam to return to its original position. As the flow of liquid from the calibration tank continues, the scale again approaches the balance condition. When balance is achieved, the poise beam again travels through its trig loop and actuates the capacitance switch, stopping the standard timer and counters. The totalized output of the flowmeter being calibrated is then compared with the calibrated weight which was added to the scale system during the calibration period. It should again be noted that since the flowmeters undergoing calibration are mass flowmeters and the basic measurement on the scale system is a weight change, no additional information or instrumentation is required to determine the calibration factor of the flowmeters being calibrated.

The entire calibration procedure is controlled from the console shown in Figure 7, which is located in the remote control building.

#### Variable Density System

Two-phase flow in a cryogenic system is generally an undesirable but often an unavoidable condition, and is particularly troublesome if it occurs in a flow measurement section. The capability of a mass flowmeter to measure the mass rate of a two-phase as well as a single phase cryogenic fluid, is a distinct advantage over any volumetric measurement system, and the capability to perform two-phase flowmeter calibrations therefore was, incorporated in the calibration system. A system schematic is shown in Figure 8.

To simplify determining the liquid-gas ratio, helium was chosen as the gas phase rather than hydrogen, since the equilibrium of a liquid-gas hydrogen mixture would be difficult to maintain under dynamic conditions. To maintain the gross system calibration accuracy, the helium gas was carried on the scale platform, so the gross scale off weight consisted of both liquid hydrogen and gaseous helium. The total mass flow through the meter was, therefore, known with the same accuracy as when performing single phase calibrations. The rate at which the helium was being injected into the system was determined by recording the pressure decay of the storage bottles supplying the gas from the calibration stand. Event markers on the pressure recording, corresponding to the start and stop null signals from the scale, identified the initial and final bottle pressure. The accuracy of the helium gas flow measurement was in the order of  $\pm 2$  to  $\pm 5\%$ , but this parameter was needed only to establish the helium-hydrogen ratio, which was of secondary value.

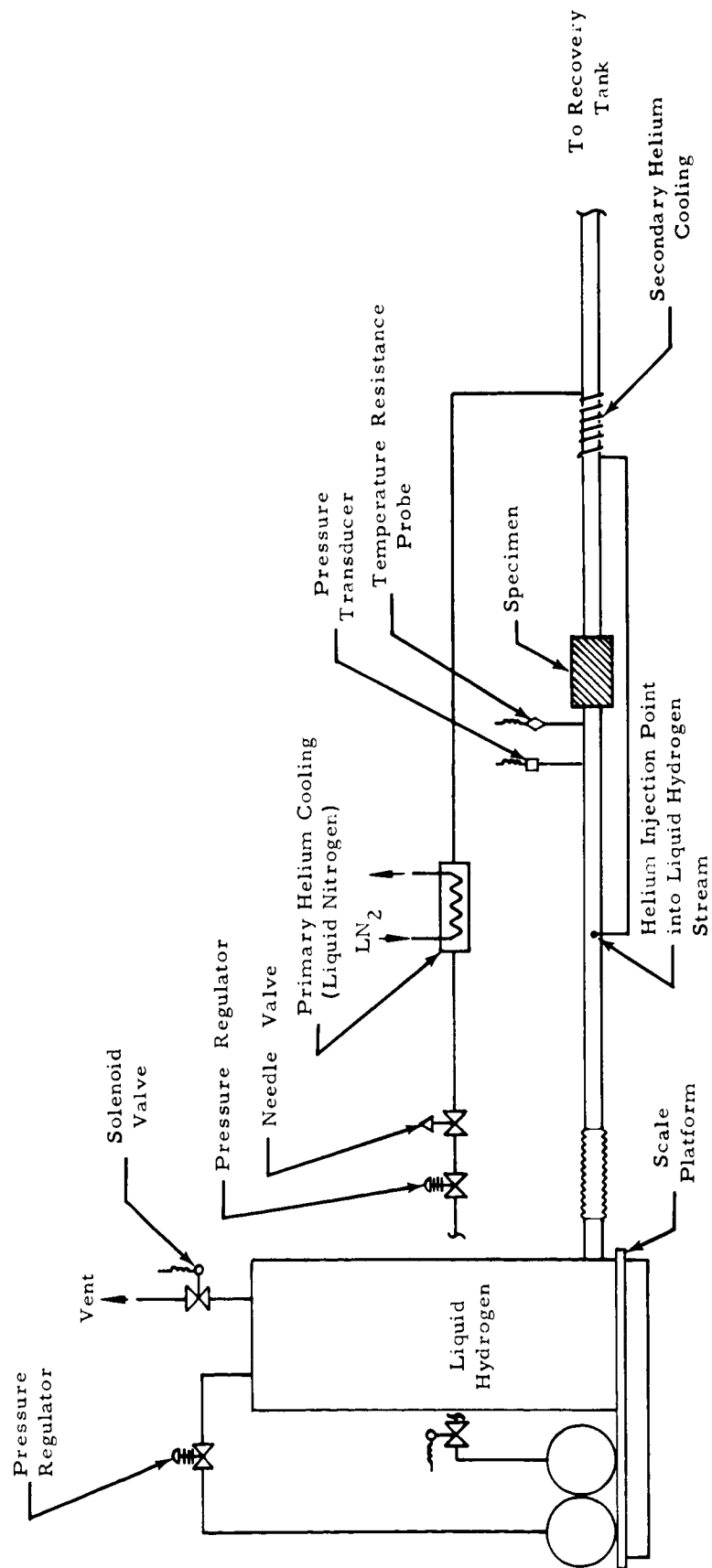


CALIBRATION SYSTEM CONTROL CONSOLE

FIGURE 7

FIGURE 8

VARIABLE DENSITY SYSTEM SCHEMATIC



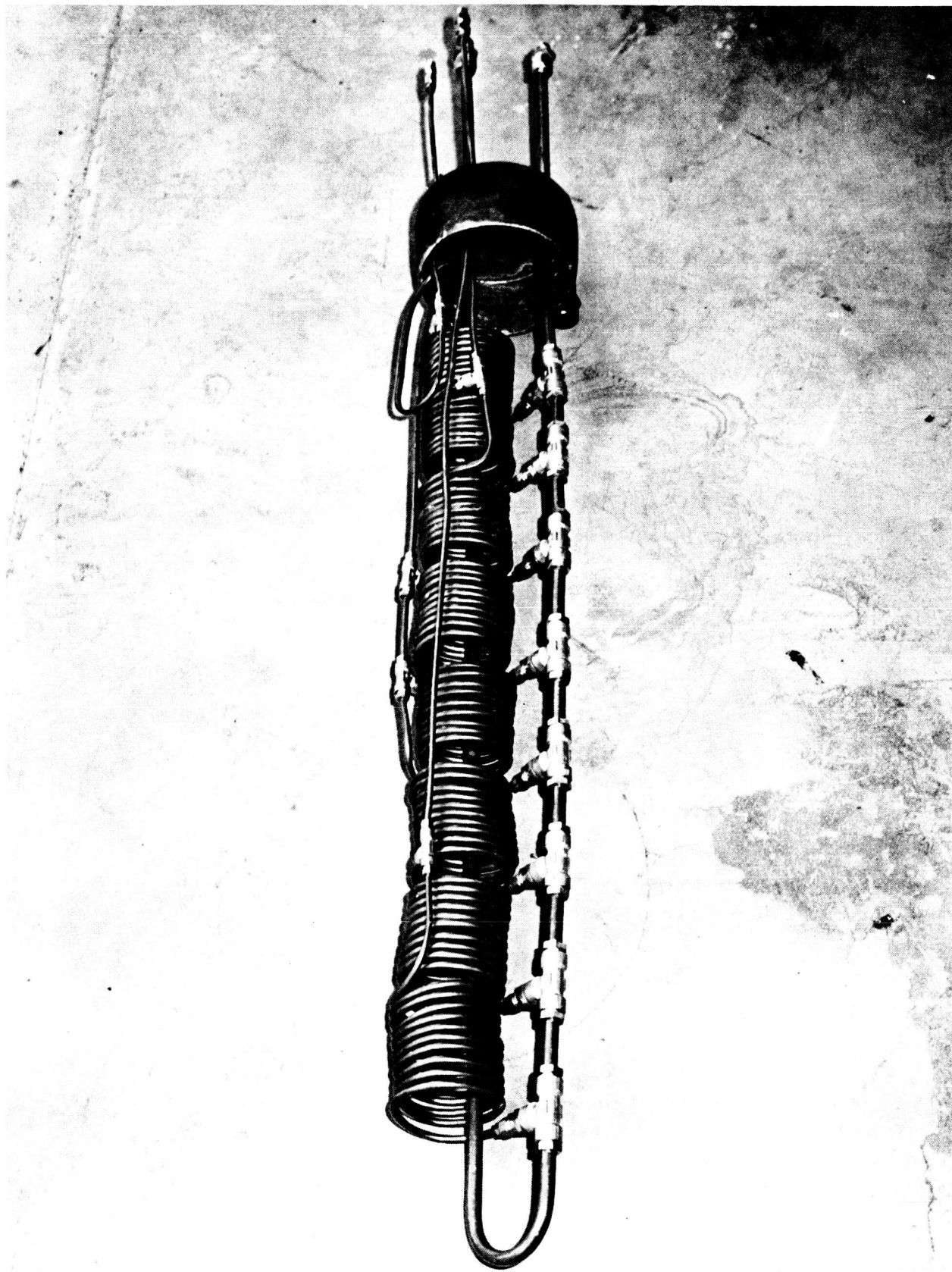
Prior to injection into the liquid hydrogen stream, the helium was pre-cooled utilizing the liquid nitrogen heat exchanger shown in Figure 9 and then subsequent cooling achieved utilizing the liquid hydrogen transfer line on the discharge side of the flowmeter as a heat sink, as shown in Figure 10. The cold helium line entered the liquid hydrogen line approximately 18 inches upstream of the flowmeter, then extended upstream an additional 42 inches, making the helium injection point 60 inches upstream of the flowmeter being evaluated.

The bulk temperature of the helium-hydrogen mixture, and the line pressure, were measured immediately upstream of the flowmeter, and these values utilized to determine the density of the two fluids. The quality of the mixture was expressed as a volumetric ratio by the following relationship:

$$X = \frac{(a/b)}{(W/G) + (a/b) - 1}$$

Where:

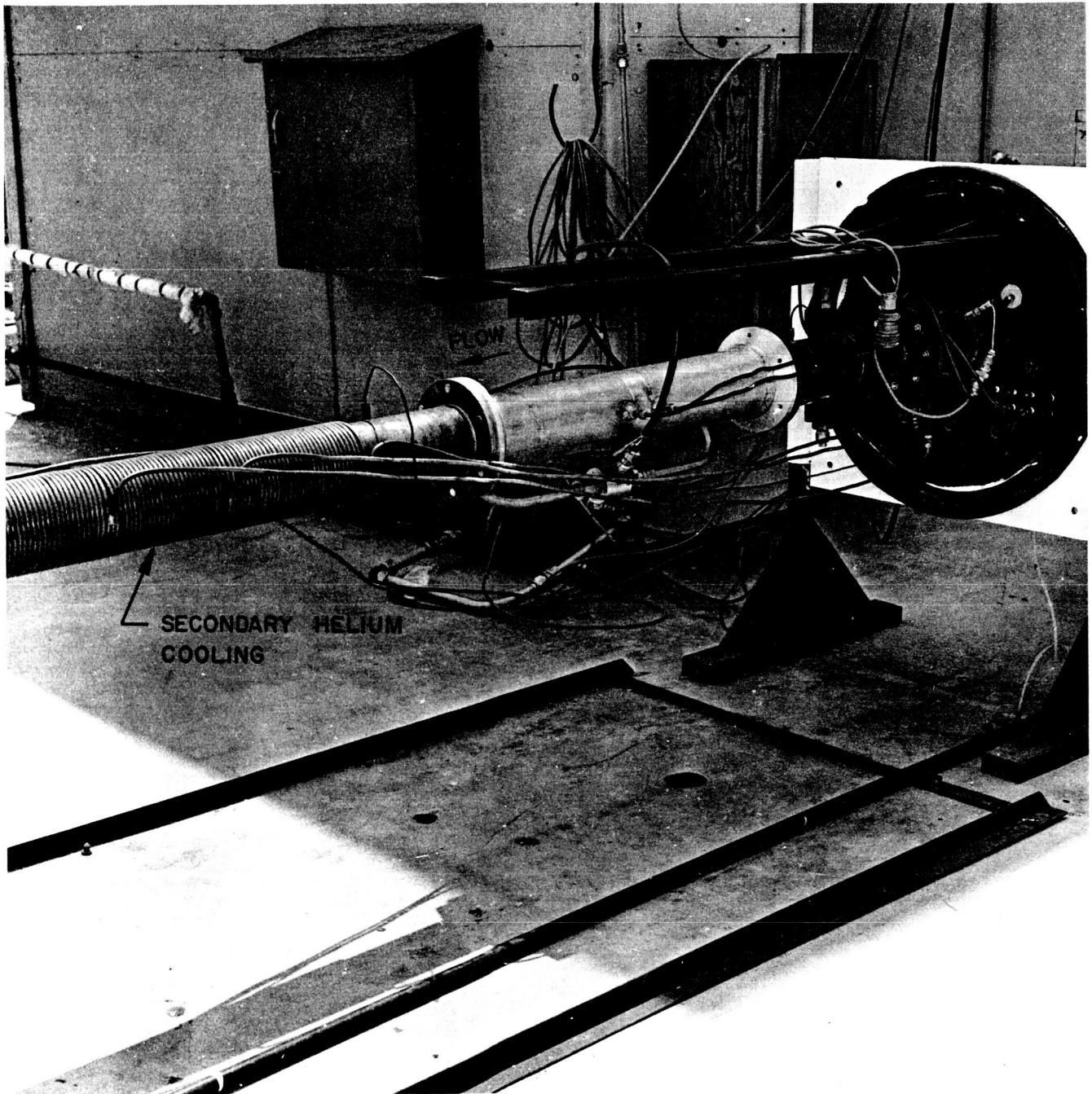
- a (lb/cu. ft) = Density of the liquid hydrogen at the pressure and temperature measured at the flowmeter inlet.
- b (lb/cu. ft) = Density of the helium gas at the pressure and temperature measured at the flowmeter inlet.
- W (lb/sec) = Total gravimetric rate as measured by the calibration stand, comprising both the liquid hydrogen and gaseous helium off weight.
- G (lb/sec.) = Gravimetric rate of helium gas as determined by the pressure decay of the scale mounted helium storage bottles.
- X = Volumetric ratio of gas to total flow, varying from 0-1.



HELIUM COOLING COILS REMOVED FROM THE LIQUID NITROGEN REFRIGERANT JACKET

FIGURE 9





HELIUM COOLING COILS SOLDERED TO THE LIQUID HYDROGEN PIPING  
DOWNSTREAM OF THE FLOWMETER

FIGURE 10



## CALIBRATION SYSTEM ERROR ANALYSIS

### Introduction

The most significant aspect of any flowmeter calibration system is the accuracy with which it is capable of measuring a given volume or mass of fluid. In addition, the operational confidence with which a single bit of data may be relied upon is extremely significant, for the most precise system imaginable would be of little value if there were no means of detecting a malfunction when it occurred. It is necessary, therefore, to provide more than one output from the system, each of which is an independent measure of the same parameter.

In the subsequent analysis, the contributing errors will be classified as (1) Systematic Errors, and (2) Random Errors, and the use of various techniques of redundant measurement will be discussed.

### Systematic Errors

The term "Systematic Error" is used to denote measurement errors which are fundamental in the analysis of the system, and are independent of any operational conditions such as cleanliness, flow rate, instrument readability, etc. These errors are fixed by the accuracy of the primary calibration, and must be considered independently from errors which result from the readability or repeatability of system components.

#### Weight Standard:

The null balance system used during the performance of this program utilizes four nominal 50-pound platform weights as its primary unit of measure. The calibration of these weights is performed periodically by the Riverside Scale Service and Los Angeles County Bureau of Weights and Measures, and are certified by these agencies to a calibration accuracy of  $\pm 0.25$  ounces per weight. The absolute error associated with these units is, therefore,  $\pm 0.0156$  pounds per 50-pound weight, or  $\pm 0.031\%$ .

#### Time Standard:

To obtain an average flow rate during a calibration run, the time interval between two null conditions must be measured. This time interval is recorded utilizing an electric timer which is periodically checked against the laboratories secondary time standard, and certified to an accuracy of  $\pm 0.030$  seconds. This time error is only significant when the flow-meter being calibrated is a rate indicating device without the capability to totalize.

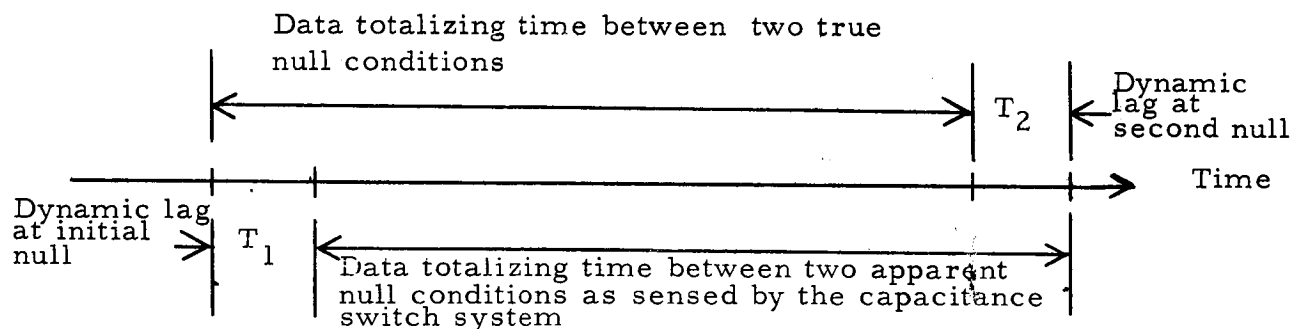
## Pressure and Temperature Standards:

Since the primary function of this calibration system was to evaluate the capability of the flowmeters to measure mass rather than volume parameters, the errors associated with pressure and temperature measurements, necessary to convert mass to volume, will not be introduced. At the conclusion of the evaluation, a statement is made defining the effect of these parameters when volume data is required.

## Random Errors

### Dynamic Lag:

The principle of operation of this calibration system is that of totalizing data from the meter being calibrated during the time interval between two null points. Each null condition is indicated by the action of a capacitance operated switch which senses the movement of the poise beam in the scale system. The linear displacement of the capacitance plates required to trigger the switch is small but not insignificant. A measurable time is required for the poise beam to travel the distance necessary to trigger the switch, and this time increment is a function of the system flow rate at the time the null point is reached. The following sketch illustrates the null-point time relationship.



From the above sketch it is readily apparent that if the time lag resulting from the motion of the poise beam is the same during the first and second null conditions ( $T_1 = T_2$ ), then the actual elapsed time between null points is the same as the apparent time between null points, and no error would exist. This is a highly idealized condition and does not occur. The non-repeatability of the distance traveled by the poise beam capacitance switch before it triggers is one source of error, and the inability of the calibration system to maintain a precisely constant flow rate, resulting in a non-repeatable accelerating torque at the null condition, is the second source of error. These two factors affecting the repeatability of the system are analyzed in the following manner.

The time required by the poise beam to travel a defined distance can be predicted utilizing the analysis presented in detail in Reference 3, and is shown to be:

$$T = \left[ \frac{6 SM}{gW} \right]^{1/3} \quad (1)$$

Where:

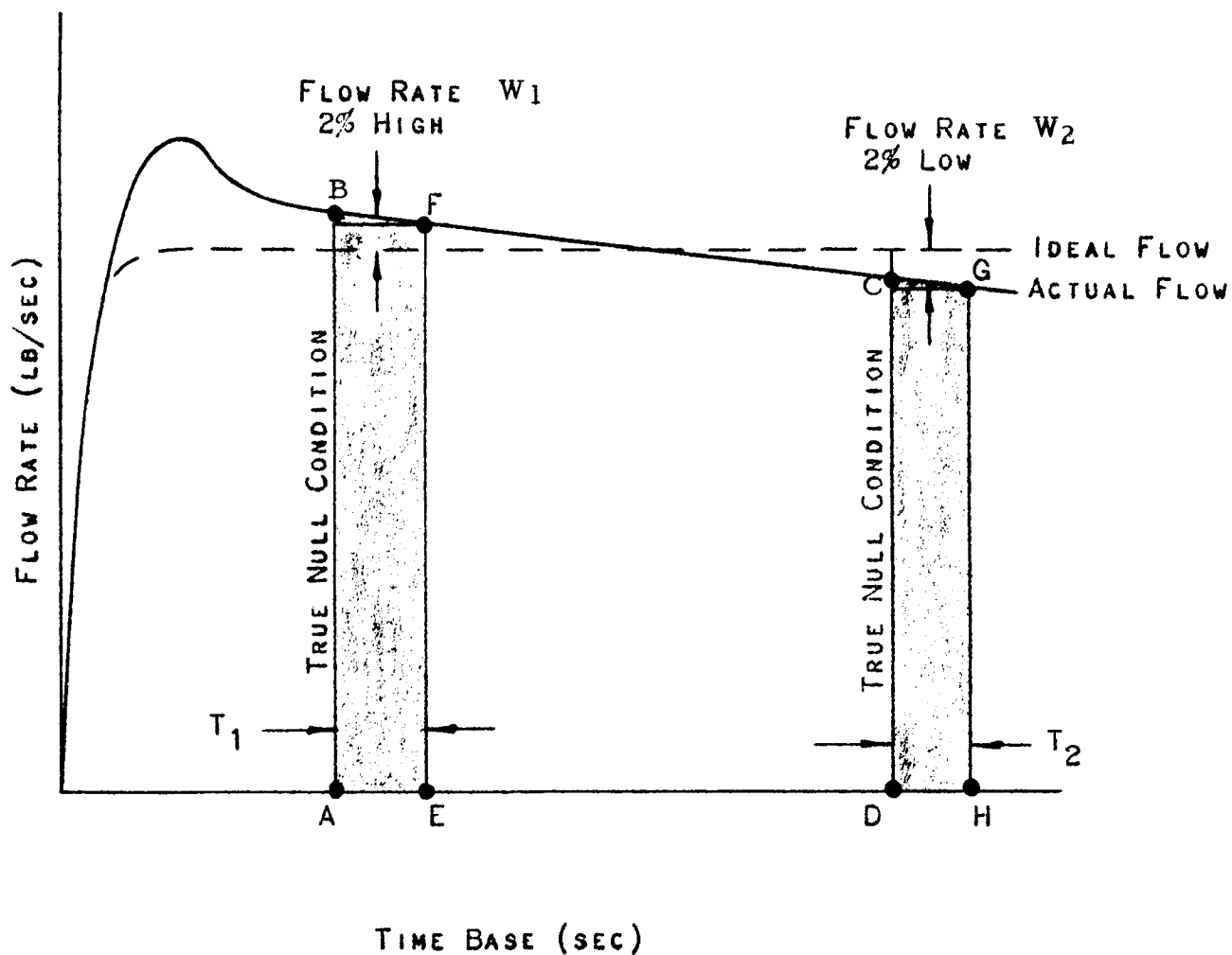
- T = lag time (sec.)
- S = Distance traveled by the poise beam before the switch triggers (ft)
- M = gross load on the scale platform (lb)
- W = transfer rate from the scale (lb/sec.)
- g = gravitational constant (32.2 ft/sec<sup>2</sup>)

With the aid of Figure 11, this relationship is expanded to express the random error associated with switch repeatability and flow instability.

During ideal flow conditions, the weight of fluid transferred during a calibration run is represented by the area ABCD. However, the actual transferred weight is approximated by the area EFGH. The difference between the ideal and actual transfer weights being the difference in areas of the shaded portions of the diagram, whose time base is denoted T<sub>1</sub> and T<sub>2</sub>.

Then:  $\Delta W = T_1 W_1 - T_2 W_2 \quad (2)$

After evaluating many calibration runs, it was determined that a conservative estimate of the flow rate stability could be established as  $\pm 2\%$ . For the purposes of this analysis, the flow rate at the initial null condition (W<sub>1</sub>) is assumed to be 1.02W and the flow rate at the final null condition (W<sub>2</sub>) is assumed to be 0.98W.



GRAPHICAL REPRESENTATION OF ERRORS CREATED BY DYNAMIC LAG AND SWITCH REPEATABILITY

FIGURE 11

Measurements performed with the poise beam capacitance switch established its operating tolerance of  $0.0012'' \pm 0.0002''$ . To maintain the worst case conditions, it will be assumed in this analysis that the distance traveled by the poise beam at the first null condition is  $0.0014''$ , and  $0.0010''$  at the second null condition.

Combining equations (1) and (2):

$$\Delta W = W_1 \left[ \frac{6S_1 M}{W_1 g} \right]^{1/3} - W_2 \left[ \frac{6S_2 M}{W_2 g} \right]^{1/3}$$

$$\Delta W = \left[ \frac{6M}{g} \right]^{1/3} \cdot \left[ W_1^{2/3} S_1^{1/3} - W_2^{2/3} S_2^{1/3} \right] \quad (3)$$

In evaluating equation (3) the following values were applied:

$$\begin{aligned} M &= 2000 \text{ lb} \\ g &= 32.2 \text{ ft/sec}^2 \\ W_1 &= (1.02) (5) = 5.10 \text{ lb/sec} \\ W_2 &= (0.98) (5) = 4.90 \text{ lb/sec} \\ S_1 &= 0.0014/12 = 0.000117 \text{ ft.} \\ S_2 &= 0.0010/12 = 0.000083 \text{ ft.} \end{aligned}$$

Resulting in an error of  $0.144 \text{ lb.}$  at a flow rate of  $5 \text{ lb./sec.}$

Applying this error of  $0.144 \text{ lb.}$  to the total transferred weight of  $200 \text{ pounds}$  results in an error of  $0.072\%$ .

Maintaining the same switch actuation and flow stability tolerances, the general term for the weighing error at any flow rate is:

$$\Delta W = (0.05) (W)^{2/3} \text{ lb}$$

or

$$\Delta W = 2.5 \times 10^{-2} (W)^{2/3} \%$$

### Scale Sensitivity:

The scale system is a specially designed mechanical beam balance, capable of supporting the total system weight and possessing a platform sensitivity of less than one ounce. Since the system is used as a null balance device, the inaccuracy introduced by the scale may be attributed solely to its repeatability. Static and dynamic tests have shown conclusively that the repeatability of the scale is greater than one ounce, thus producing an error at the initial and final null points of  $\pm 0.03\%$  for a 200-pound weight change.

### Extraneous Loading:

The effects of extraneous horizontal and vertical loading of the scale system have been evaluated experimentally by the application of loads in excess of those encountered during the system's operation, and with the calibration tank both pressurized and unpressurized. This evaluation demonstrated that the scale system sensitivity is not reduced during operation by extraneous loading.

### Summary of Errors for Mass Flowmeter Calibration System

The resultant effect of systematic and random errors in the calibration system are summarized below for a mass flow rate of 5 pounds per second.

TABLE 4

#### Summary of Random and Systematic Errors

	<u>Error (%)</u>
A. Random Errors	
Initial scale balance	$\pm 0.03$
Final scale balance	$\pm 0.03$
Dynamic lag and capacitance switch	$\pm 0.07$
	<hr/>
Maximum random error:	$\pm 0.13\%$
RMS random error:	$\pm 0.082\%$
B. Systematic Error	
Standard weight	$\pm 0.03$

The preceeding summary of random and systematic errors indicates an expected performance on the order of  $\pm 0.1\%$ . Actual operation of the system during the past 30 month period and numerous static and dynamic evaluations of the system substantiate the above analyses.

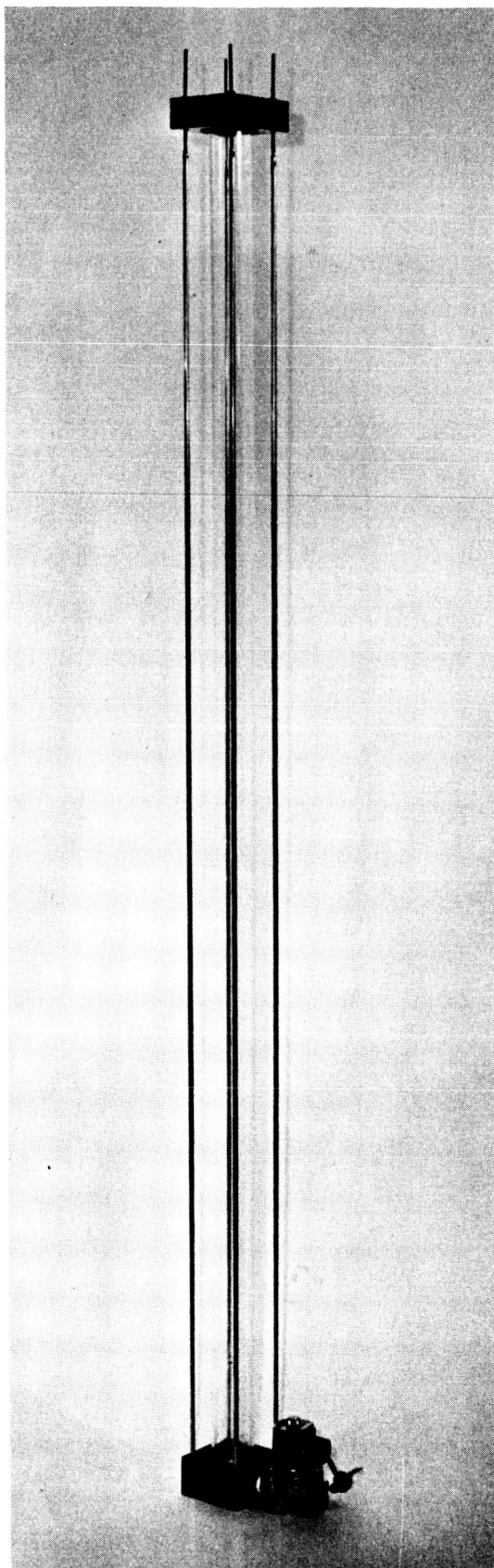
In order to gain further insight into the dynamic performance of the calibration system, and to provide a means whereby the system performance could be quickly evaluated on a periodic basis, a prover system was fabricated which would provide a means of quickly evaluating the scale system sensitivity and repeatability (including capacitance switch).

This prover consists of a vertical transparent tube, closed at the bottom by a one-inch solenoid valve. This valve is actuated by the same relay in the instrumentation circuit which gates all timing and totalizing equipment utilized in the calibration system, which is controlled by the capacitance switch in the scale poise beam housing. The prover tube is shown in Figure 12, and the system block diagram in Figure 13.

To operate the prover, the transparent tube is filled to approximately  $3/5$  capacity with water, and the scale roughly balanced by adjusting the poise beam weights. The tube is then filled to capacity with water, which puts the scale in an overweight condition. A switch in series with the gating relay and the solenoid valve is closed and the valve opens, allowing the water to drain out of the tube and off the scale platform. When sufficient water has drained from the system to cause the scale to pass through the null balance point, the gating relay opens and the solenoid valve is closed.

By observing the water level in the transparent tube and marking the meniscus, a reference data point is obtained. The tube is then refilled and, without adjusting the scale poise weights, the test repeated. If the system were 100% repeatable, the solenoid valve would be closed by the gating relay when the weight on the platform was exactly the same, and the water level in the tube would be at the same point.

Tabulated data of test results obtained with the calibration system sensitivity prover are presented in Table 5.



CALIBRATION SYSTEM PROVER

FIGURE 12



FIGURE 13  
CALIBRATION PROVER BLOCK DIAGRAM

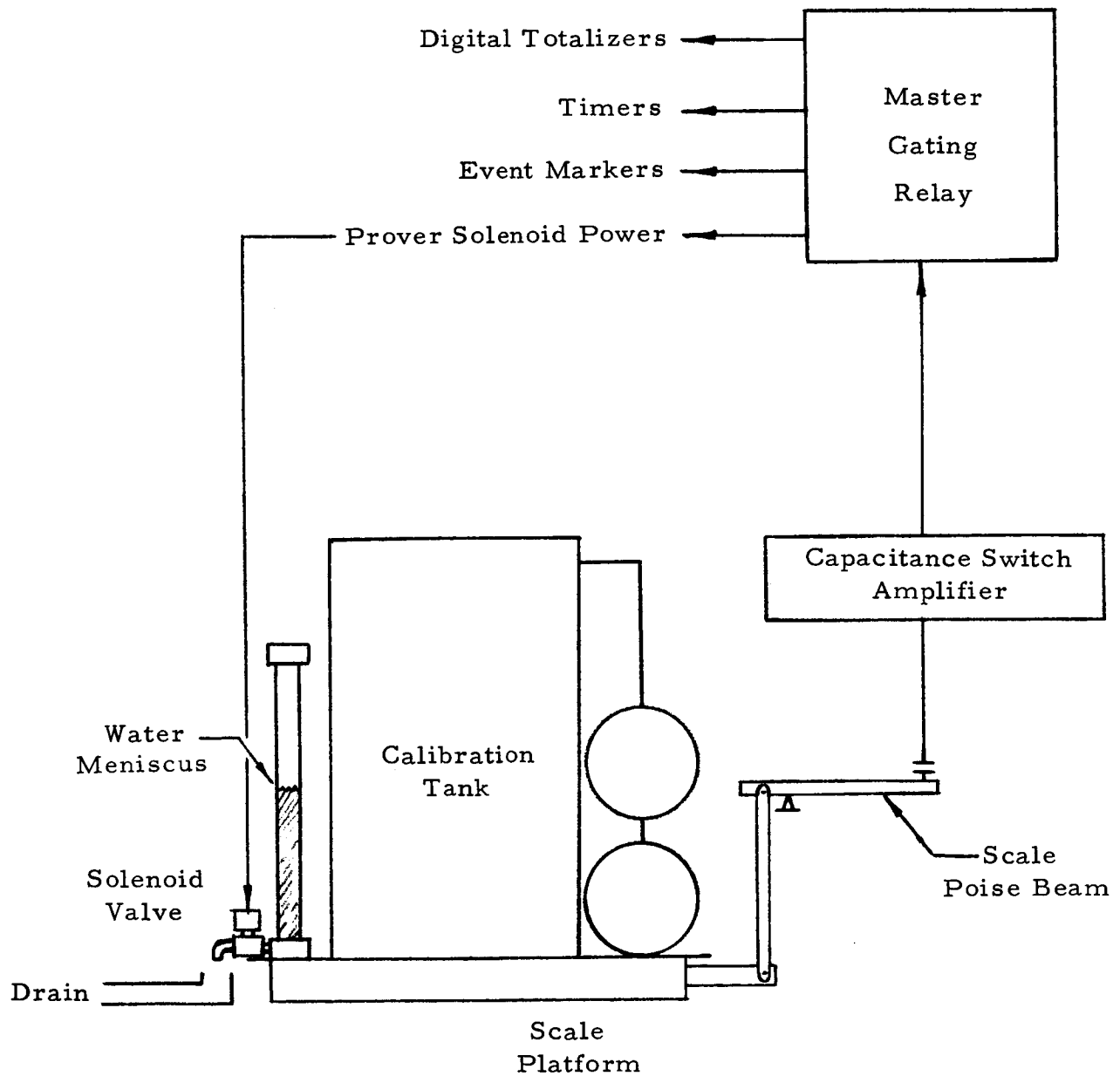


TABLE 5

TABULATION OF TEST RESULTS OBTAINED WITH THE  
CALIBRATION SYSTEM SENSITIVITY PROVER

Test No.	Water Level Deviation (inches)	Corresponding Wt. Deviation (lbs)	Error (%)
1	-0.12	-0.014	-0.007
2	+0.72	+0.085	+0.043
3	+1.18	+0.139	+0.070
4	-0.64	-0.076	-0.038
5	+0.33	+0.039	+0.019
6	+0.40	+0.047	+0.024
7	-0.04	-0.005	-0.003
8	-0.52	-0.061	-0.030
9	+0.22	+0.026	+0.013
10	-0.10	-0.012	-0.006
11	+0.30	+0.035	+0.018
12	-0.34	-0.040	-0.020
13	+0.46	+0.054	+0.027
14	-0.20	-0.024	-0.012
15	+1.10	+0.130	+0.065
16	-0.85	-0.100	-0.050
17	-0.24	-0.028	-0.014
18	+0.18	+0.021	+0.011
19	-0.58	-0.068	-0.034
20	+0.26	+0.031	+0.016

Note: The percent error is based on the 200 pound transfer weight used during flowmeter calibrations.

## EVALUATION OF THE DECKER CORPORATION GYROSCOPIC MASS FLOWMETER

### Description

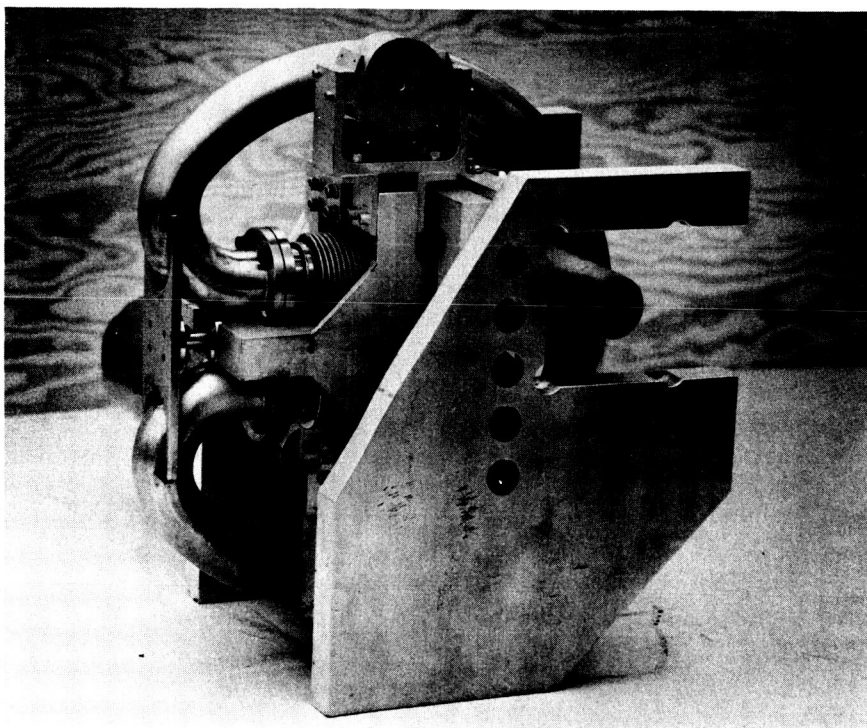
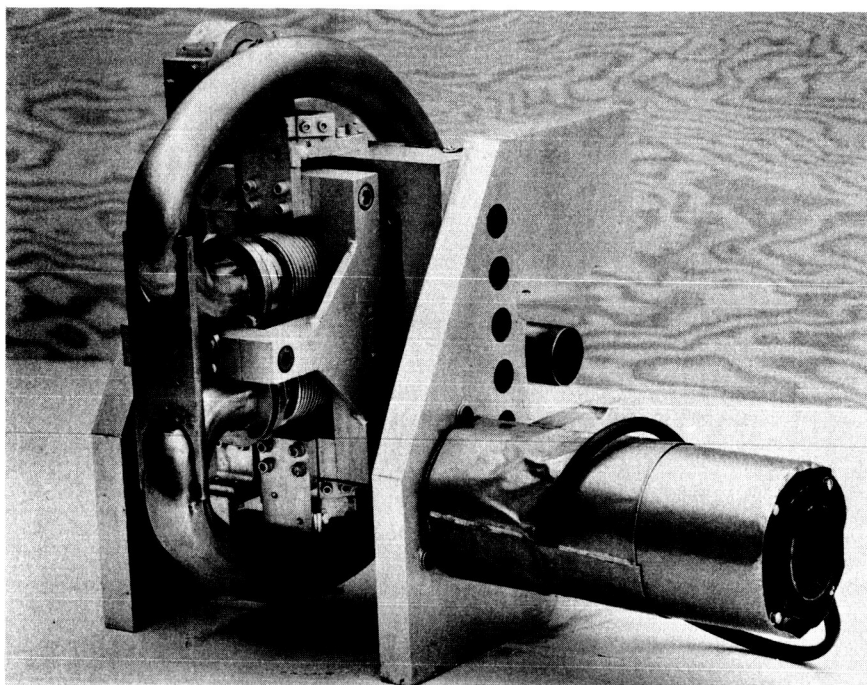
The Decker mass flowmeter operates on the classical principle of the gyroscope, in which the flowing liquid is caused to traverse a circular path simulating the rotating flywheel. The circular loop of the flowing liquid is forced to precess in an oscillating manner through the use of a mechanical vibration link. As a result of the forced precession, an orthogonal torque is produced in the flow loop which is also sinusoidal in nature. The resultant torque is restrained by linear torsion members, with the resultant displacement in the orthogonal plane a linear measure of the mass flow rate. The Decker mass flowmeter which was evaluated in the current program is shown in Figures 14 and 15.

Attractive features of the Decker mass flowmeter may be briefly summarized as follows:

1. Experimental results obtained by the Decker Corporation, indicate performance to within  $\pm 0.5\%$  using water as the test medium, over an extreme flow range.
2. Absence of internal obstructions or rotating assemblies in the fluid stream.

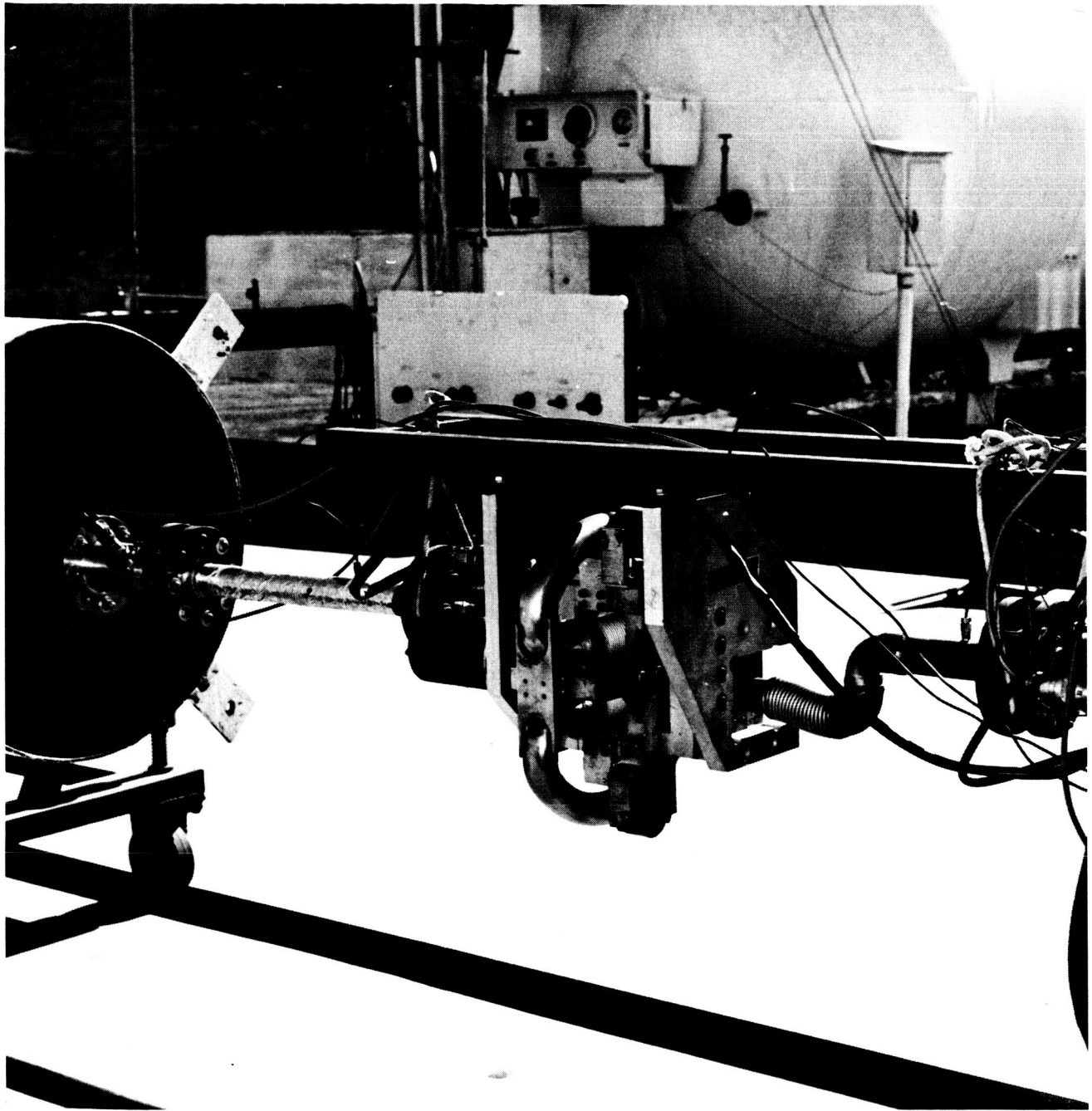
The Decker mass flowmeter system possesses several characteristics, as outlined below, which might be considered undesirable in certain applications:

1. Basic output signal from the flowmeter is 0 to 50 mv, which is subsequently digitized in an analog to digital conversion circuit for totalizing.
2. Large, bulky physical configuration which is unsuitable for flight applications.
3. Requires the use of a motor-drive assembly.



THE DECKER CORPORATION VIBRATING GYROSCOPIC MASS FLOWMETER

FIGURE 14



THE DECKER FLOWMETER IN THE  
CALIBRATION SYSTEM

FIGURE 15

## Discussion of Test Data

Preliminary tests were conducted with the Decker gyroscopic flowmeter on November 15, 1961, utilizing liquid nitrogen as the test medium. These tests were performed in order that a comparison might be obtained with the liquid hydrogen data to be generated in subsequent tests. During the liquid nitrogen calibration, it was noted that at flow rates above 5 pps, mechanical binding was occurring between the coil and permanent magnet of the motion transducers. This condition was attributed to the thermal contraction of the flowmeter's housing and subsequent reduction in clearance within the transducers. During these calibrations 18 test points were obtained between 1.2 and 5.2 pps, with the resulting data presented in Table 6 and Figures 16 and 17. This preliminary data indicated linear flowmeter characteristics, however, the data scatter was approximately  $\pm 2\%$ . The majority of this scatter was attributed to binding resulting from thermal contraction of the flowmeter housing which was not severe enough to fully restrict the motion of the unit, but which would induce a random data scatter.

As a result of the restriction occurring in the flowmeter's transducers during the liquid nitrogen calibration, the flowmeter was returned to the manufacturer and the clearances increased between the coil and permanent magnet.

The first liquid hydrogen calibrations were attempted on March 1, 1962. The first problem to arise during this series of tests was the formation of frost on the flowmeters motion transducers, resulting from a poor vacuum seal on the test chamber. In an effort to reduce the frost formation, the test chamber vacuum was broken and a helium purge directed on the two transducers. Simultaneously, it was noted that the flowmeter's solid state integrator system was being saturated by background vibrations generated by the high line velocity.

Subsequent calibrations were attempted March 3, 1962, however, before any data was obtained, the flowmeter drive motor froze and testing was terminated. It was determined that the elimination of the vacuum system and the introduction of helium gas to prevent frost formation on the motion transducers allowed sufficient heat transfer away from the drive motor to cause the grease lubricated bearings to freeze. The flowmeter was returned to the manufacturer and non-lubricated bearings installed in the drive motor assembly. During this modification, the solid state integrator was replaced with a vacuum tube unit to alleviate the saturation problem.

On May 11, 1962 additional liquid hydrogen testing was performed with the modified drive motor and vacuum tube integrator system. After obtaining eleven valid calibration points a leak developed in the flowmeter isolation bellows and testing was terminated. This data is presented in Table 7 and Figures 18 and 19. This limited data was encouraging in that the scatter was found to be approximately  $\pm 1.4\%$  as opposed to the  $\pm 2\%$  observed during the liquid nitrogen calibrations. With the exception of three data points, the distribution fell within a band of approximately  $\pm 0.9\%$ .

The cognizant representatives of the Decker Corporation felt that prior to performing additional calibrations, the flowmeter pivot support assemblies should be modified to give increased sensitivity.

Modification of the flowmeter pivot support assembly was completed and the flowmeter returned for further evaluation in December, 1962. To further assist in evaluating the performance of the flowmeter, a volumetric turbine type flowmeter was installed downstream of the Decker unit and the two units calibrated simultaneously.

The data obtained during these tests was not as satisfactory as that obtained during the May 11 calibrations. As noted in Figures 20 and 21, considerably more data scatter was encountered. The installation of the volumetric flowmeter did, however, substantiate the performance of the calibration stand and eliminate that variable from the analysis. A composite plot of the two flowmeters performance during this last calibration is shown in Figure 21.

Pressure drop data obtained during the calibration is presented in Figure 22.

TABLE 6  
DECKER GYROSCOPIC MASS FLOWMETER  
MODEL 600-1  
LIQUID NITROGEN CALIBRATION  
15 NOVEMBER 1961

Point No.	System Rate (lb/sec)	Decker Meter Rate (lb/sec)	Decker Meter Constant (pps/pps)
2	4.6514	3.2860	0.70645
4	4.5504	3.2626	0.71699
5	4.7459	3.3528	0.70646
7	3.8261	2.7510	0.71901
8	3.3370	2.4574	0.73641
9	1.7193	1.2509	0.72756
10	1.8981	1.3619	0.71751
11	1.5803	1.1077	0.70094
13	1.8269	1.2091	0.66183
14	2.2328	1.5897	0.71198
16	3.0722	2.2105	0.71952
17	4.8527	3.4867	0.71851
18	1.2639	0.8333	0.65931
19	3.6060	2.5620	0.71048
20	2.2648	1.5341	0.67737
21	2.7629	1.9574	0.70846
25	2.6473	1.7980	0.70585
26	5.1089	3.5682	0.69843

Note: The flowmeter inlet conditions were maintained at  $45 \pm 5$  psia and  $38 \pm 0.5^\circ\text{R}$ .



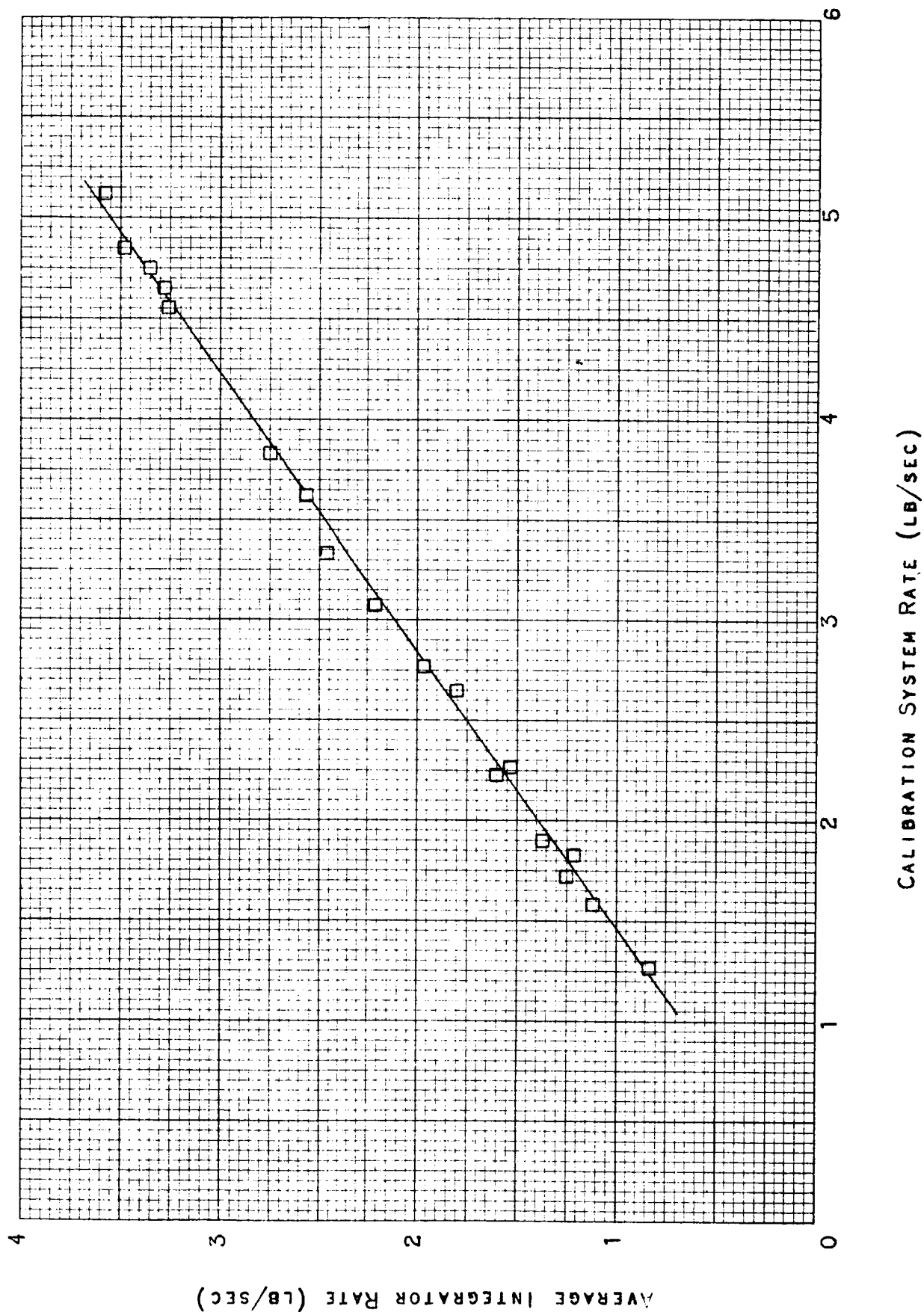
FIGURE 16

DECKER GYROSCOPIC MASS FLOWMETER

MODEL 600-1

LIQUID NITROGEN CALIBRATION

15 NOVEMBER 61



DECKER GYROSCOPIC MASS FLOWMETER

MODEL 600-1

LIQUID NITROGEN CALIBRATION

15 NOVEMBER 61

FIGURE 17

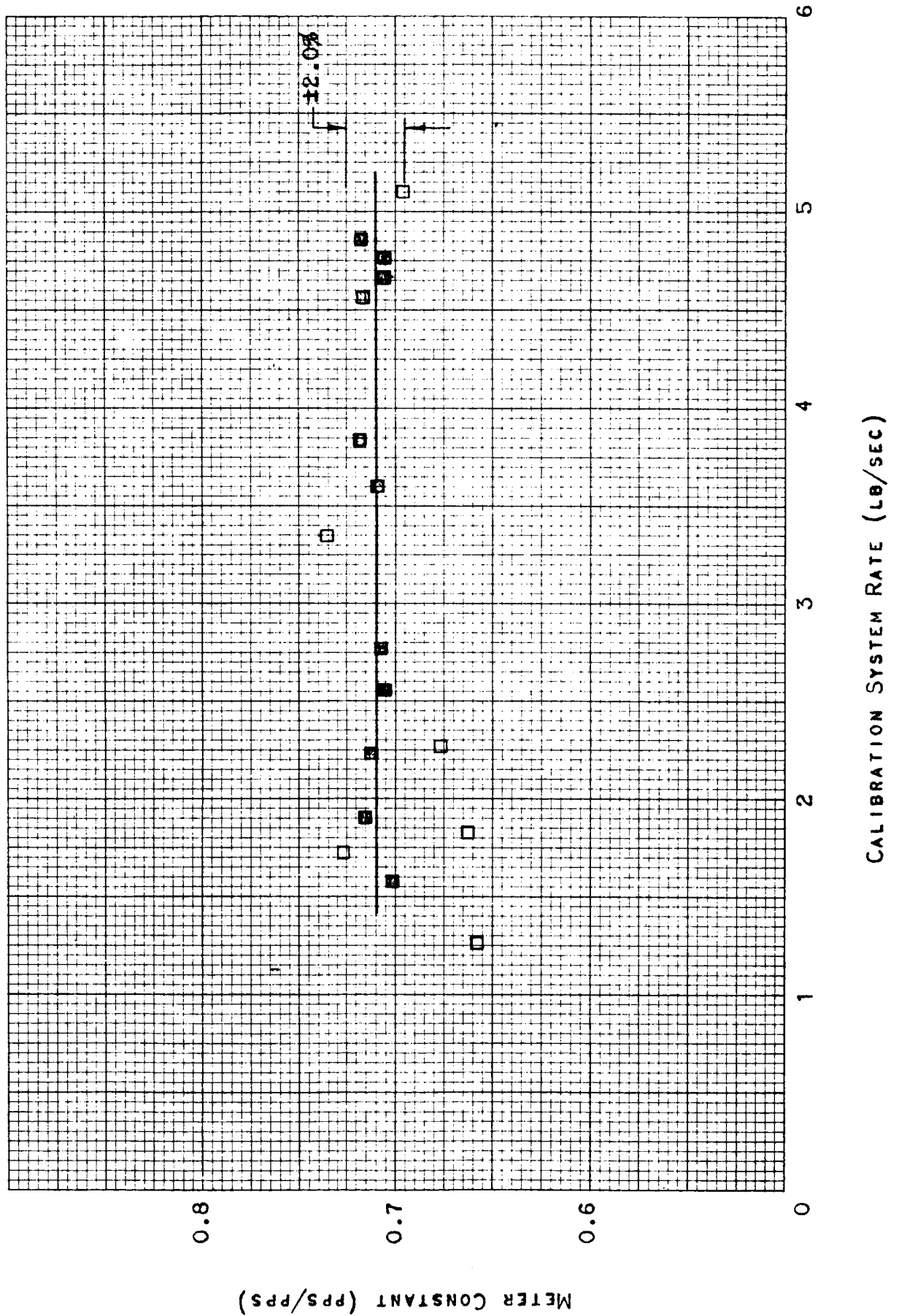


TABLE 7  
DECKER GYROSCOPIC MASS FLOWMETER  
MODEL 600-1  
LIQUID HYDROGEN CALIBRATION  
11 MAY 1962

Point No.	System Rate (lb/sec)	Decker Meter Rate (lb/sec)	Decker Meter Constant (pps/pps)
1	3.057	3.281	1.0733
2	2.794	3.079	1.1020
3	2.479	2.537	1.0234
4	2.991	3.180	1.0632
5	0.602	0.469	0.7791
7	1.893	1.900	1.0037
8	1.267	1.252	0.9882
9	1.403	1.386	0.9879
12	3.928	4.221	1.0746
13	4.030	4.397	1.0911
14	3.908	4.189	1.0719

Note: The flowmeter inlet conditions were maintained at  $45 \pm 5$  psia  
and  $38 \pm 0.5^{\circ}\text{R}$ .

DECKER GYROSCOPIC MASS FLOWMETER

MODEL 600-1

LIQUID HYDROGEN CALIBRATION

11 MAY 62

50

AVERAGE INTEGRATOR RATE (LB/SEC)

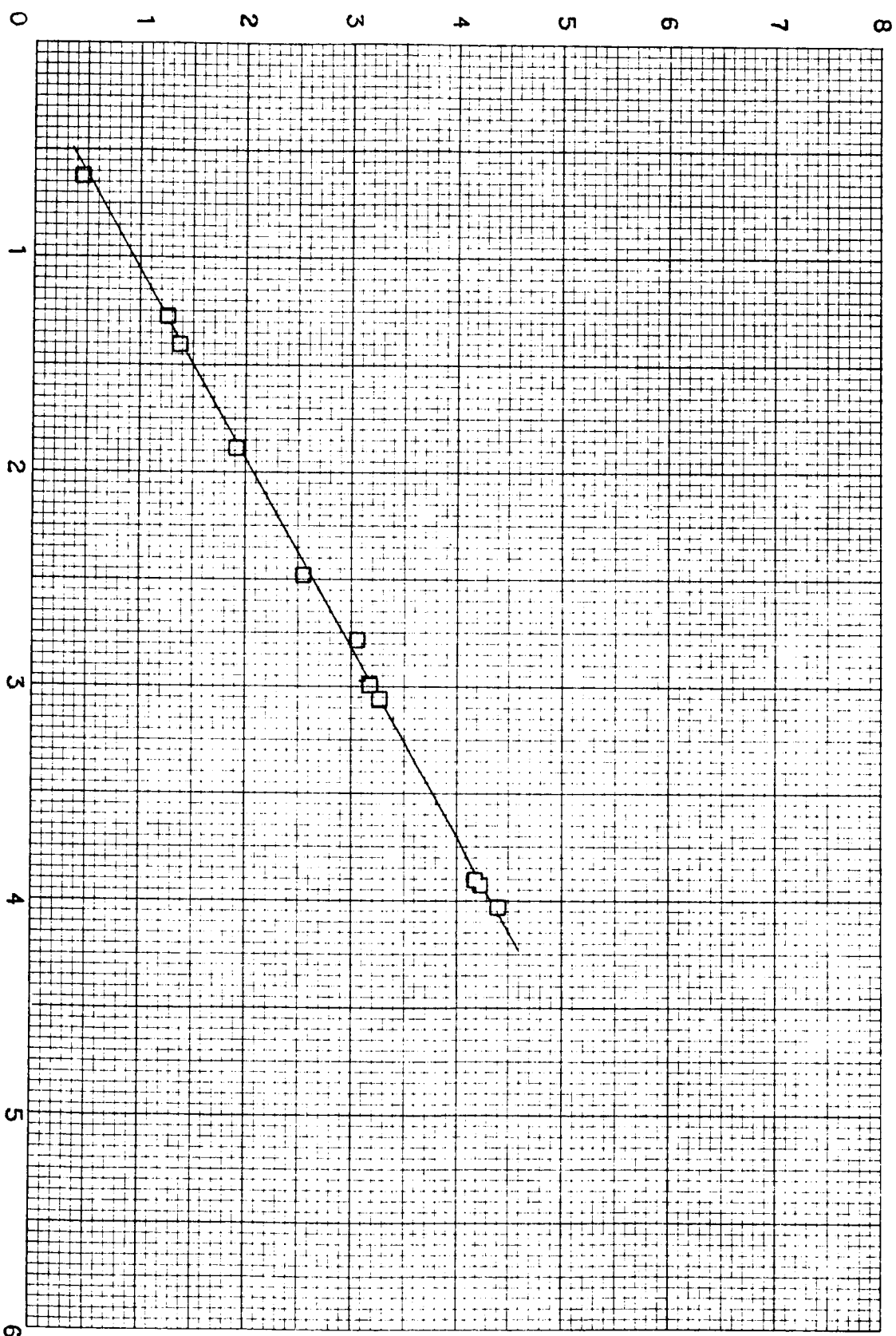


FIGURE 18

CALIBRATION SYSTEM RATE (LB/SEC)

DECKER GYROSCOPIC MASS FLOWMETER

MODEL 600-1

LIQUID HYDROGEN CALIBRATION

11 MAY 62

FIGURE 19

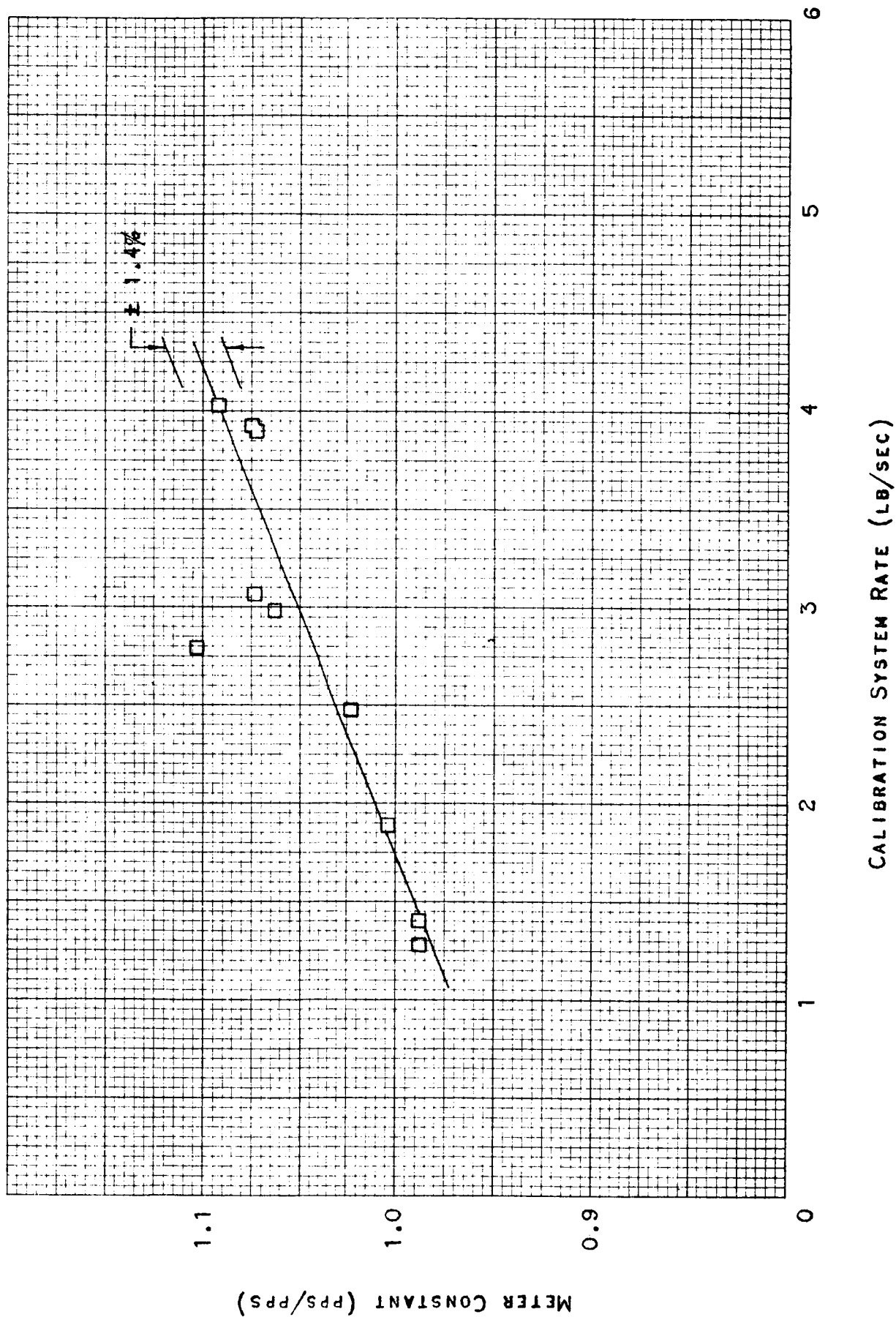


TABLE 8

DECKER GYROSCOPIC MASS FLOWMETER  
MODEL 600-1  
LIQUID HYDROGEN CALIBRATION  
21 DECEMBER 1962

Point No.	System Rate (lb/sec)	Decker Meter Rate (lb/sec)	Decker Meter Constant (pps/pps)	Backup Potter Meter Constant (cycle/lb)
1	3.244	2.621	0.8080	23.855
2	3.272	2.722	0.8319	23.674
3	3.762	3.416	0.9080	23.709
4	3.777	3.178	0.8414	23.724
5	4.328	3.800	0.8780	23.870
6	1.041	0.554	0.5322	23.378
7	1.090	0.869	0.7972	23.202
8	1.611	0.508	0.3153	23.539
9	1.610	0.893	0.5547	23.393
10	2.203	1.567	0.7113	23.428
11	2.207	1.821	0.8251	23.338

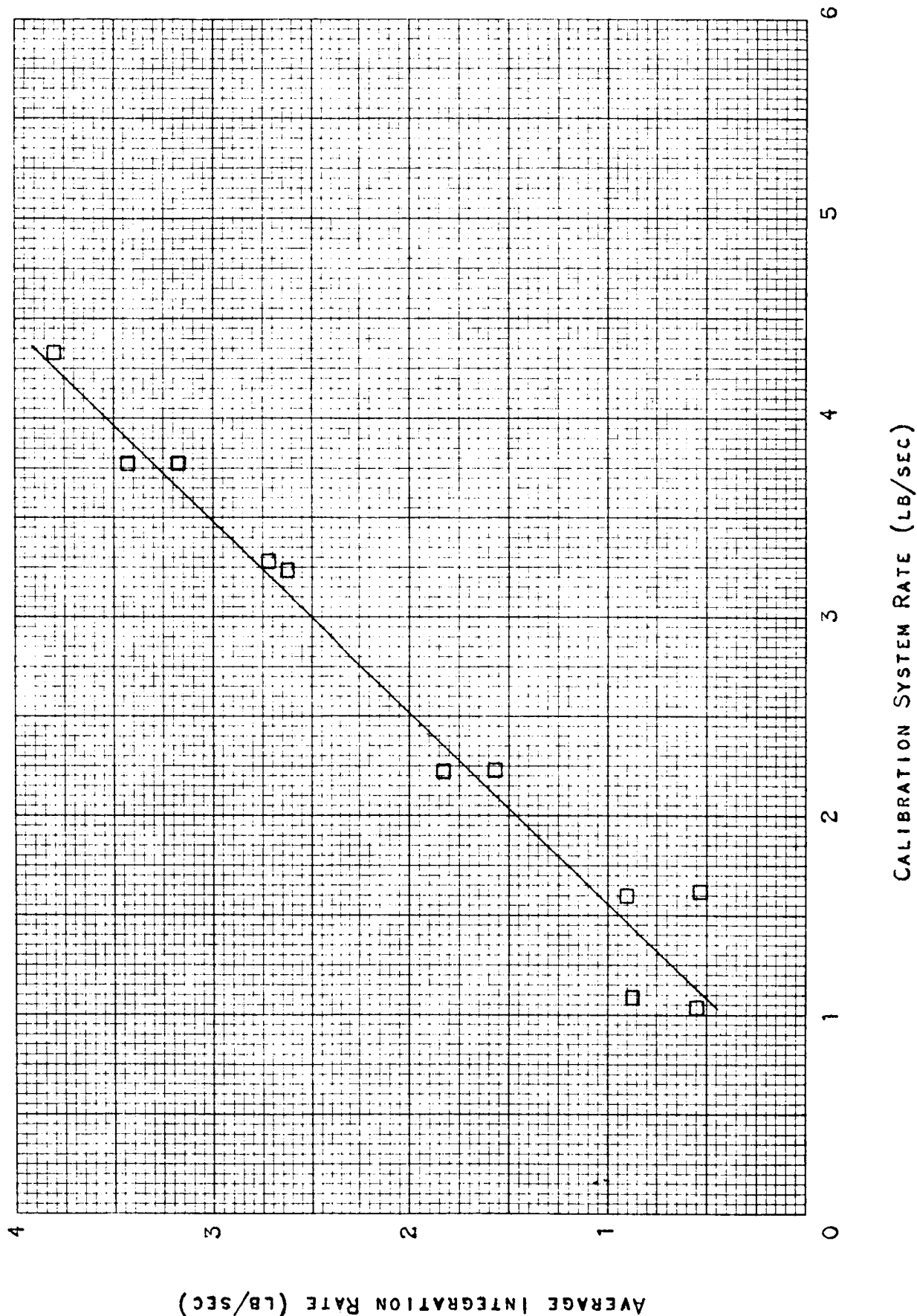
Note: The flowmeter inlet conditions were maintained at  $45 \pm 5$  psia  
and  $38 \pm 0.5^{\circ}\text{R}$ .

DECKER GYROSCOPIC MASS FLOWMETER

MODEL 600-1

LIQUID HYDROGEN CALIBRATION

21 DECEMBER 62



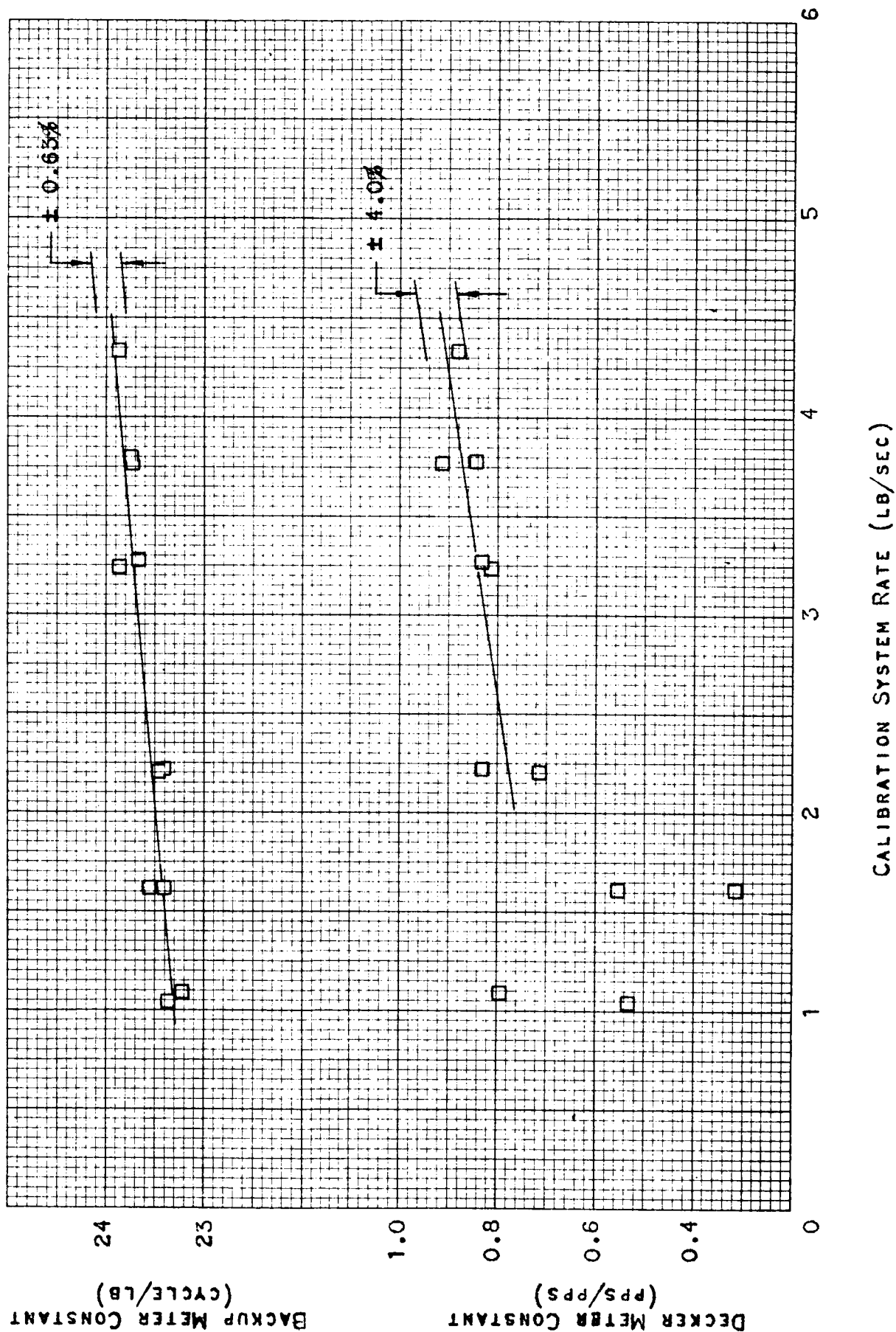
DECKER GYROSCOPIC MASS FLOWMETER

MODEL 600-1

LIQUID HYDROGEN CALIBRATION

21 DECEMBER 62

FIGURE 21





DECKER GYROSCOPIC MASS FLOWMETER  
 MODEL 600-1  
 LIQUID HYDROGEN PRESSURE DROP CHARACTERISTICS

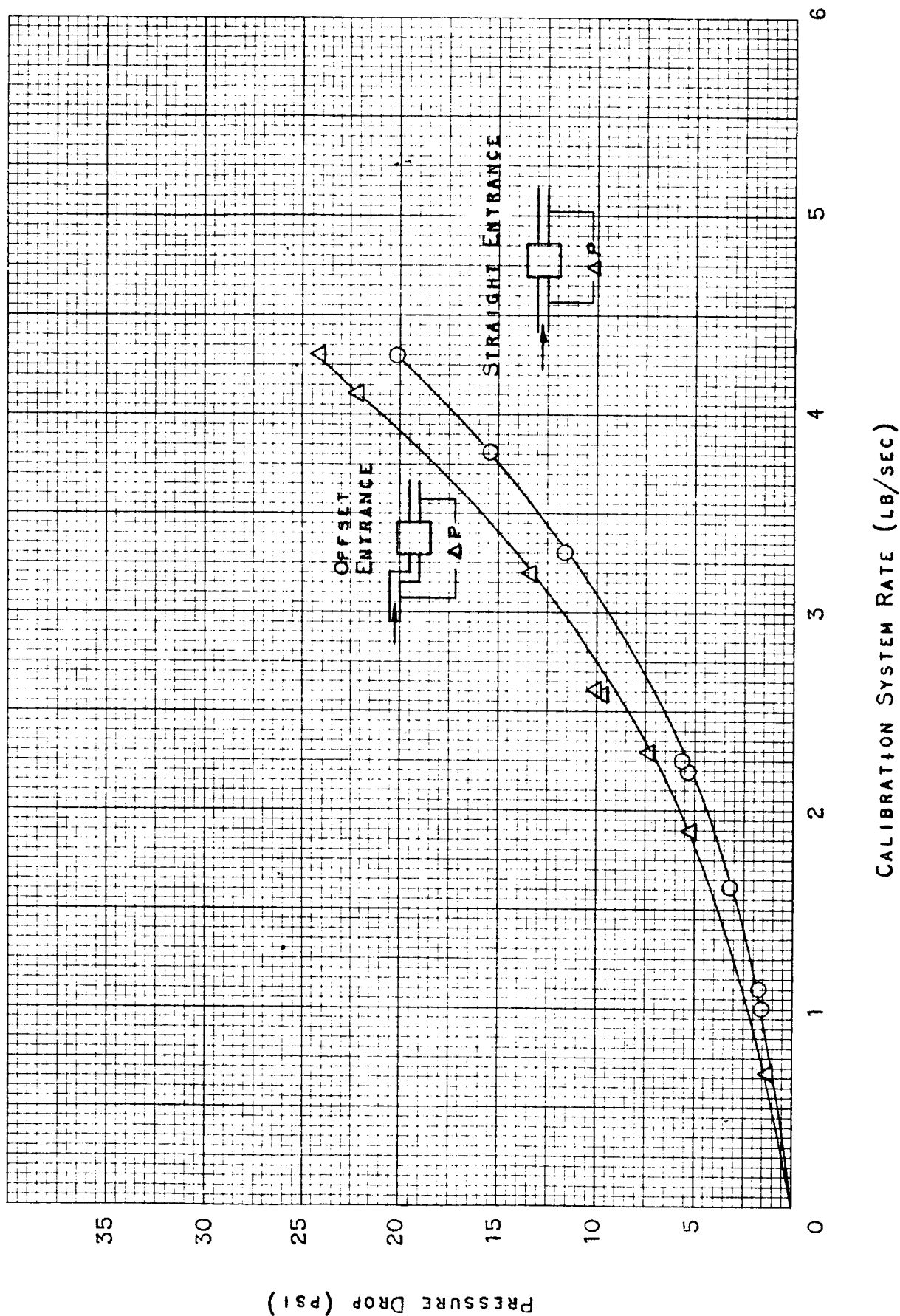


FIGURE 22

## EVALUATION OF THE POTTER AERONAUTICAL CORPORATION TWIN TURBINE MASS FLOWMETER

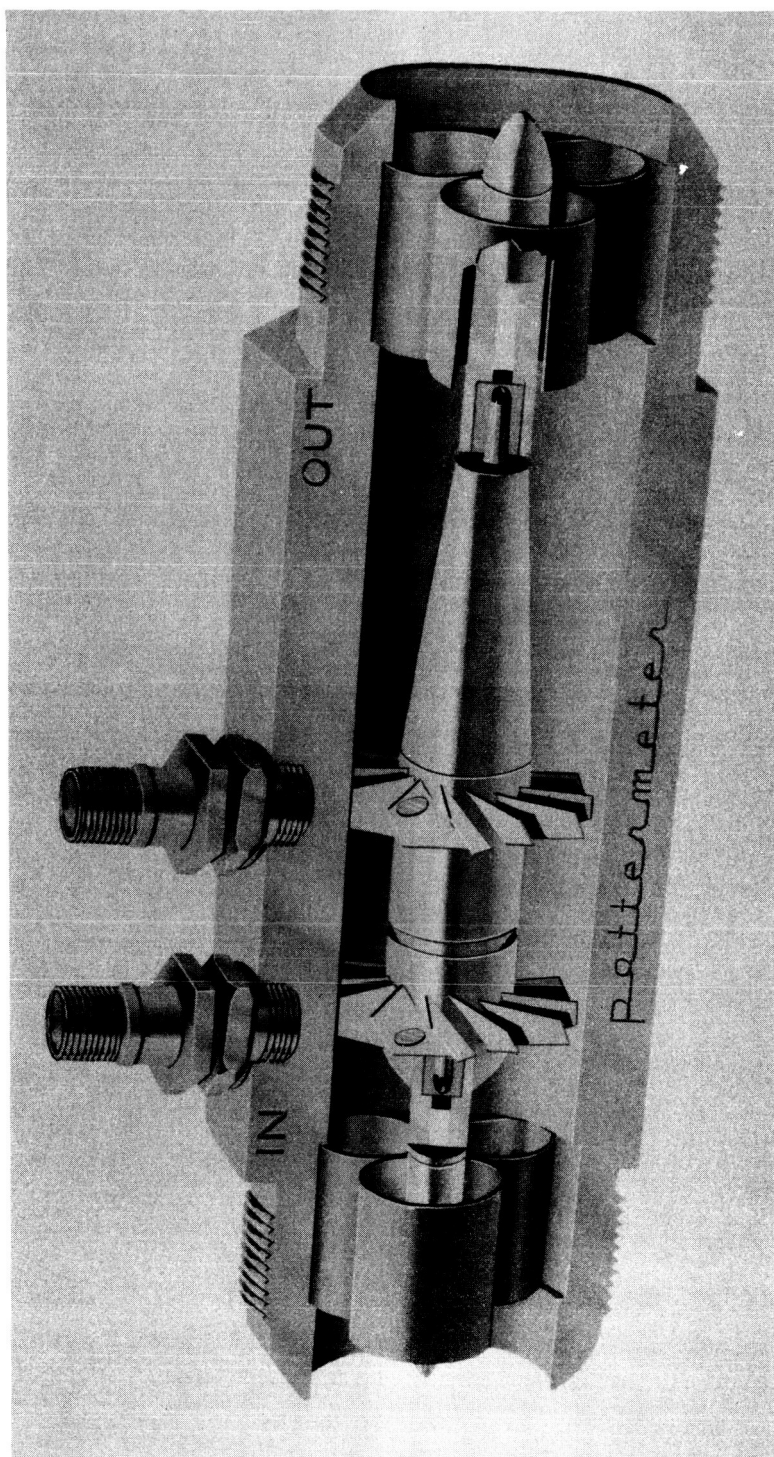
### Description

The Potter mass flowmeter design is based on established principles of volumetric turbine flowmeter design with a unique adaptation to provide mass flow rate measurement. The mass flowmeter, shown in Figures 23 and 24, consists of two axial turbine assemblies coupled through a linear torsion spring, and supported by a common pair of bearings.

The upstream turbine is designed with a greater blade angle than the downstream turbine, and would rotate at a greater angular velocity if it were not for the linear torsion coupling, which forces the two turbines to rotate at a common average velocity. The torsional restraint offered by the torsion member may be shown to be proportional to the mass flow momentum of the stream, and the phase angle between the upstream and downstream turbine assembly to be proportional to the mass flow momentum. Since the velocity of the coupled turbine assembly is proportional to the volumetric flow rate, the period between the passing of a fixed reference point on the upstream turbine and a fixed reference point on the downstream turbine is proportional to the mass flow rate. This time period is referred to as  $(T)$ .

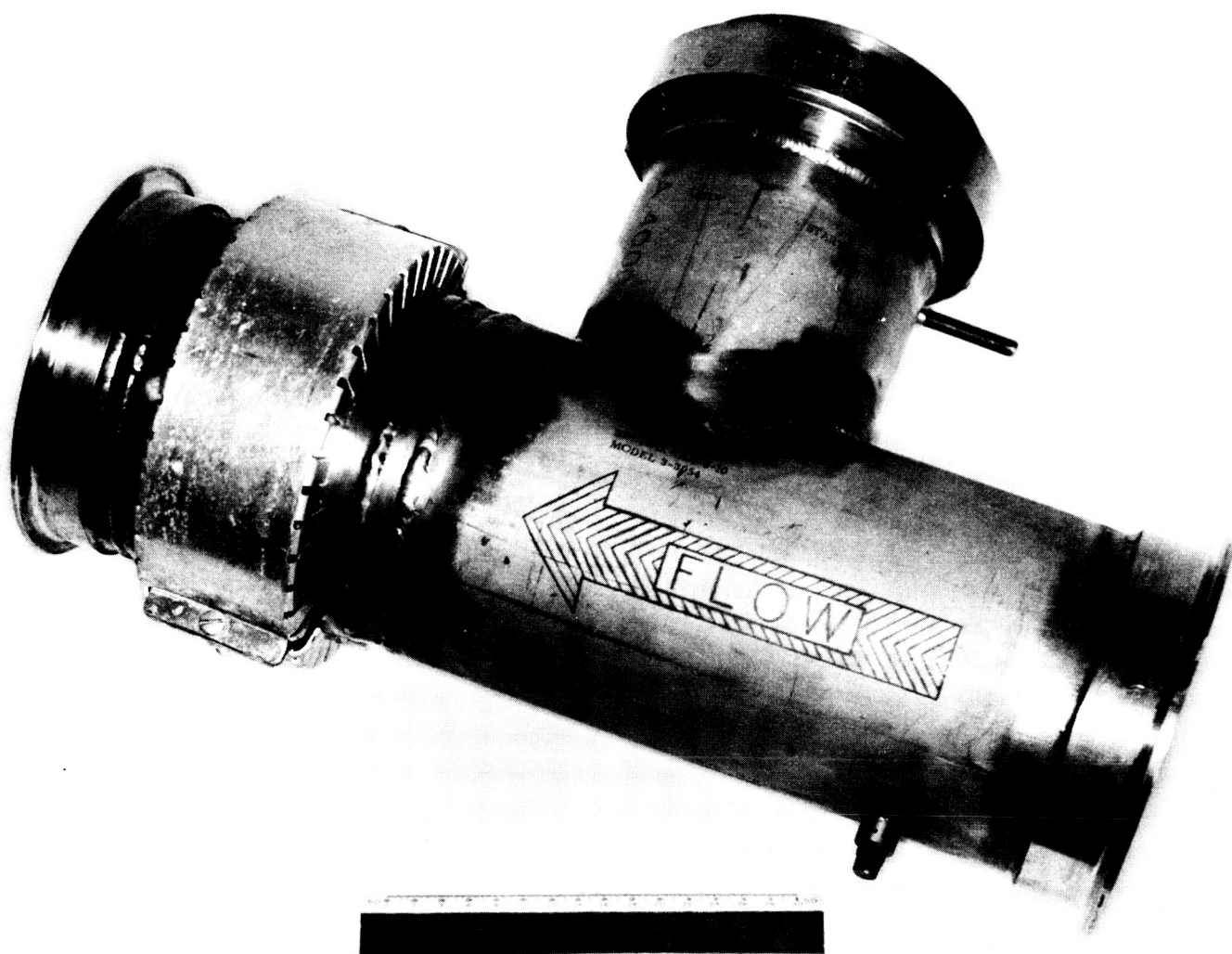
The advantages of the Potter mass flowmeter system may be briefly summarized as follows:

1. The flowmeter design is relatively simple and is passive in nature.
2. Experimental results indicate an expected performance within +0.5%.
3. Provides both digital volume information and digital mass flow information.
4. Conventional turbine design offers nominal pressure loss.



POTTER TWIN TURBINE MASS FLOWMETER

FIGURE 23



THE 3-INCH POTTER TWIN TURBINE MASS FLOWMETER

FIGURE 24

The Potter mass flowmeter system possesses several characteristics, as outlined below, which might be considered undesirable in certain applications:

1. The turbine assembly, in the present configuration, may be subject to overspeeding during cooldown operations in cryogenic applications.
2. The flow range is limited by the displacement angle between the two turbines, which is proportional to the mass flow momentum.
3. Accurate measurement of the time period between the two turbine assemblies may be difficult in some applications.

It should be noted that the initial flowmeter submitted by the Potter Corporation for evaluation during this program was a nominal 1-1/2" unit and was, at the time, the smallest mass flowmeter which Potter had manufactured. It became apparent during the course of the program that a great number of the problems encountered with the flowmeter were primarily a result of the flowmeter size. As a result of these initial difficulties, the latter portion of the program was conducted with a 3" diameter flowmeter.

#### Discussion of Test Data Obtained with the 1-1/2 Inch Flowmeter

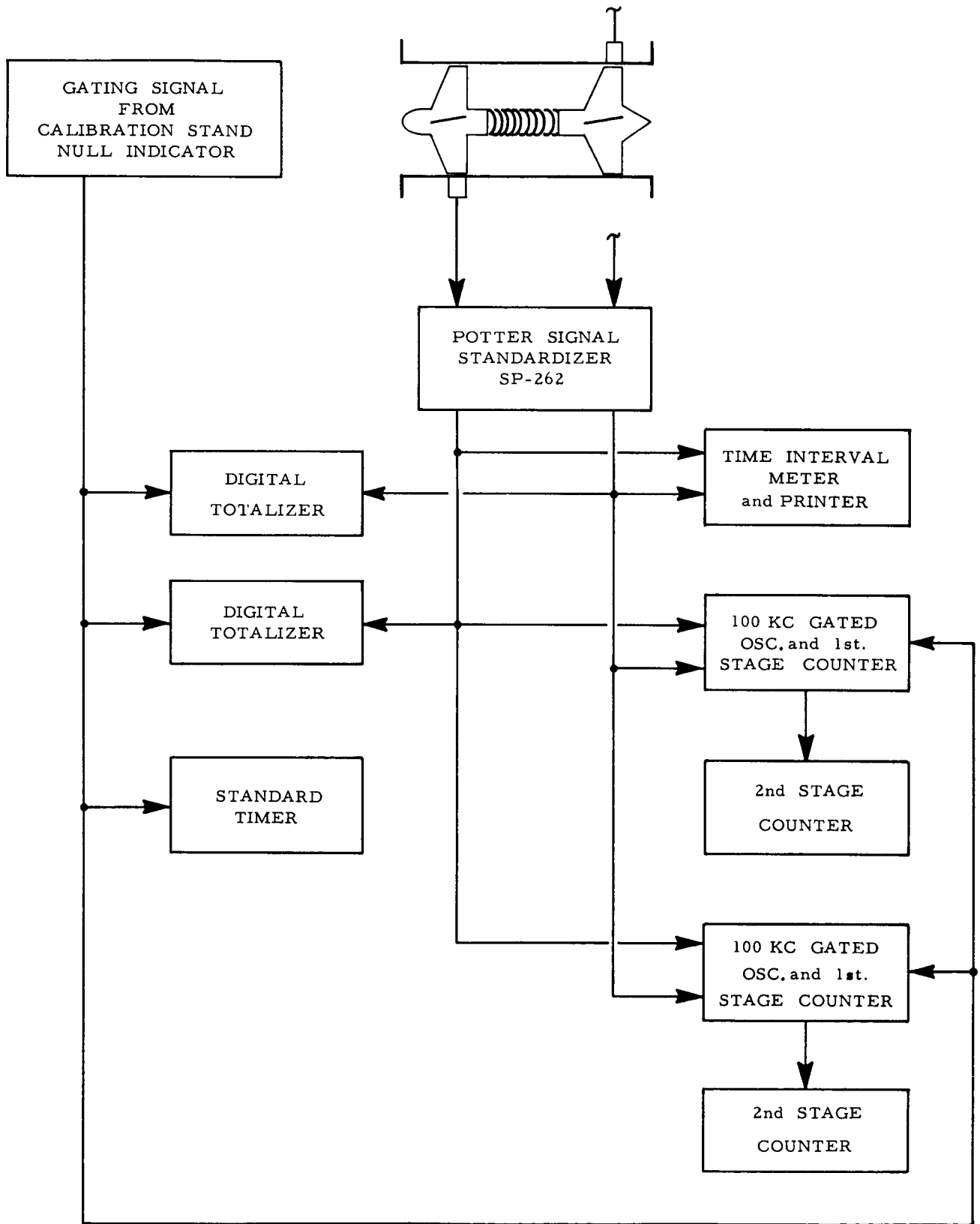
The basic instrumentation utilized during the calibration of the Potter twin turbine mass flowmeter is shown in Figure 25, consisting primarily of standard timing and digital totalizing equipment. The only unique equipment required was the Potter Signal Standardizer. The function of this component is to condition the output pulse from the flowmeter's magnetic pick-up to provide a 12 volt, 0.3 microsecond pulse.

Before installing the flowmeter in the calibration system, the flowmeter was submerged in liquid nitrogen and manually rotated with no detectable binding due to thermal contraction.

The initial liquid nitrogen calibration resulted in extremely scattered and unpredictable data. Subsequent evaluation of the instrumentation revealed that the 100 KC gated oscillators used as the high frequency time base for integrating the mass output of the flowmeter were not sufficiently stable under varying load conditions to maintain the necessary calibration accuracy. Prior to performing additional calibrations, two Ransom Research digital counters, which incorporated 100 KC oscillators were installed in the system. These units also supplied the first stage digital counting. Potter digital counters were utilized for the second stage of the totalizing system resulting in a capacity of 14 digits.

FIGURE 25

INSTRUMENTATION UTILIZED DURING THE CALIBRATION OF THE POTTER MASS FLOWMETER



The first 10 data points obtained during the liquid nitrogen calibration of February 13, 1962, were performed with the two signal leads from the flowmeter to the signal standardizer reversed, resulting in the measurement of the back angle of the turbine displacement. The leads were reversed and subsequent calibrations performed. During the subsequent calibrations that date, it was noted that the turbine displacement was decreasing with increasing flow rate, contrary to the intended operational characteristic of the flowmeter.

At this time it was felt that a bench check should be made of the flowmeter to determine that the electronic system, as installed, was capable of displaying the true performance of the flowmeter. To accomplish this, the two turbine systems were carefully displaced approximately 80° and locked into position with two pieces of lead wire. Using the flowmeter's air spin port, the turbine assembly was rotated at various velocities, and the fixed phase angle calculated from the digital output obtained from the instrumentation. The results of this check showed conclusively that over the entire rotational velocity range of the flowmeter an accurate and repeatable measure of the turbine displacement could be obtained utilizing the existing system.

The flowmeter was then disassembled and the ball bearings in the torsion member removed and immersed in liquid nitrogen. No evidence of stiffness or binding was observed, and this possible explanation for the behavior of the flowmeter was discarded.

Additional evaluation of the data obtained during the liquid nitrogen calibrations was performed by the manufacturer's representatives present during the program. From available pressure drop characteristics which had been obtained during development water calibrations, it was concluded that cavitation was probably occurring between the first and second turbine stages, as a result of the low pressures at which the liquid nitrogen calibrations were performed.

Although no conclusive liquid nitrogen calibration data had been thus far obtained, it was felt that the liquid nitrogen calibrations had provided an opportunity to solve many of the mechanical and electronic system problems which were originally encountered.

The initial liquid hydrogen calibration was attempted in March, 1962; however, as a result of moisture in the torsion housing, the flowmeter had to be removed from the system and vacuum baked prior to additional liquid hydrogen work.

The data obtained during the subsequent liquid hydrogen calibration was found to be extremely erratic. The flowmeter was removed from the system and the bearings examined by the Potter representative. It was determined that bearings with increased tolerances should be installed and the flowmeter was returned to Potter for modification.

With the opened tolerance bearings installed in the flowmeter, a third calibration was performed resulting in the same erratic performance noted during the preceding calibrations. In an effort to isolate the problem, the output of the Signal Standardizer was monitored on a dual beam oscilloscope. It was clearly apparent that the aluminum "non-magnetic" turbine blades were producing minor pulses which were very close to the minimum gating voltage of the Signal Standardizer. It was reasoned that these secondary pulses were gating the standardizer in a random fashion resulting in apparent erratic flowmeter performance.

Prior to performing subsequent liquid hydrogen calibrations, a Carpenter-20 turbine assembly was substituted for the aluminum assembly used during the initial calibrations. In addition, the opened tolerance bearings were replaced by a full complement less three ball bearings in a roller bearing race assembly.

Subsequent operation of the flowmeter revealed that the Carpenter-20 rotor assembly also exhibited magnetic properties at liquid hydrogen temperatures. While observing the output from the Signal Standardizer on the oscilloscope during the system cooldown, sharp isolated peaks were observed corresponding to the magnetic blade of each turbine until the system temperature reached approximately  $-178^{\circ}\text{F}$ . At this temperature, secondary pulses corresponding to each "non-magnetic" turbine blade were observed. At  $-346^{\circ}\text{F}$  the secondary pulses were  $1/2$  the magnitude of the primary signal, and at  $-375^{\circ}\text{F}$  the primary and secondary signals were indistinguishable. Again, the flowmeter was removed from the system, returned to Potter and a turbine assembly of a Type 316 stainless steel installed.

With the Type 316 stainless steel turbine assembly installed in the flowmeter, the first successful calibration data was obtained April 25, 1962 and is presented in Figure 26. The repeatability of the mass rate data was approximately  $\pm 5.0\%$ , and the repeatability of the volume data, uncorrected for density changes, was approximately  $\pm 0.4\%$ . It was the opinion of the manufacturer that the excessive mass rate data scatter was the result of bearing drag, and that the full complement less three bearings should be replaced by full complement less one bearing. This modification was performed May 1, 1962 and an additional 19 calibration points obtained.



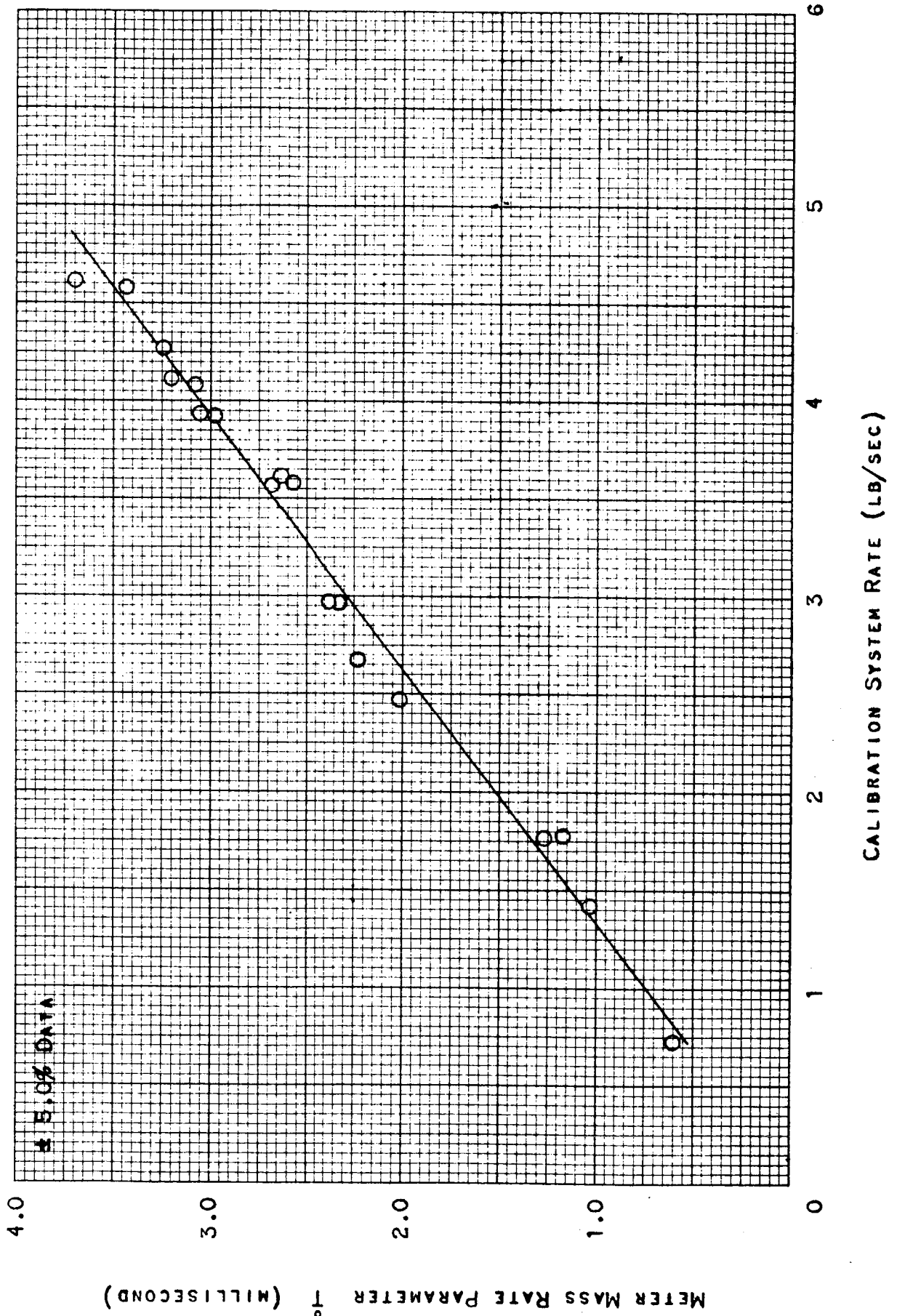
FIGURE 26

POTTER TWIN TURBINE MASS FLOWMETER

MODEL 1.5-3030, SERIAL PD-1.5-29

LIQUID HYDROGEN CALIBRATION

25 APRIL 62



As anticipated, there was a considerable improvement in the repeatability of the flowmeters mass rate output, which can be seen by comparing Figures 26 and 27. Above 1.5 lb/sec., 93% of the data fell in a band of  $\pm 1.8\%$ .

To further substantiate the flowmeter performance, additional calibration points were attempted in the 3 to 5 lbs. per second range. Shortly after initiating the additional points both pick-up coils became inoperative and future testing was postponed until replacement coils could be obtained.

On May 17, 1962, new pick-up coils were installed in the flowmeter and approximately 20 calibration points obtained. During these tests a noticeable shift in the calibration data was observed and again a significant increase in data scatter noted. The flowmeter was removed from the system and upon inspection of the bearings, evidence of excessive wear and galling was noted. The flowmeter was returned to the manufacturer for installation of new bearing assemblies prior to performing additional evaluation tests.

After replacing the worn bearings a series of successful calibrations was performed in November, 1962 and the results presented in Table 9 and Figures 28 through 31.

The data obtained November 15, indicated an extremely non-linear performance at flowrates in excess of 4 lbs. per second. Possible cause for the non-linear characteristic was attributed to increased thrust load on the bearings at high flow rates. Additional calibration points were performed on November 16, during which excellent calibration data was obtained below 4 lbs. per second with non-linear performance again occurring at flowrates above 4 lbs. per second. During the performance of additional calibration tests performed on November 21, a malfunction in the calibration readout equipment precluded obtaining more than two valid test runs. In subsequent discussions with the cognizant MSFC personnel, a decision was reached to terminate further testing of the 1-1/2" mass flowmeter and perform all subsequent calibration tests with a 3" diameter mass flowmeter which was then available.

POTTER TWIN TURBINE MASS FLOWMETER  
MODEL 1.5-3030, SERIAL PD-1.5-29  
LIQUID HYDROGEN CALIBRATION

1 MAY 62

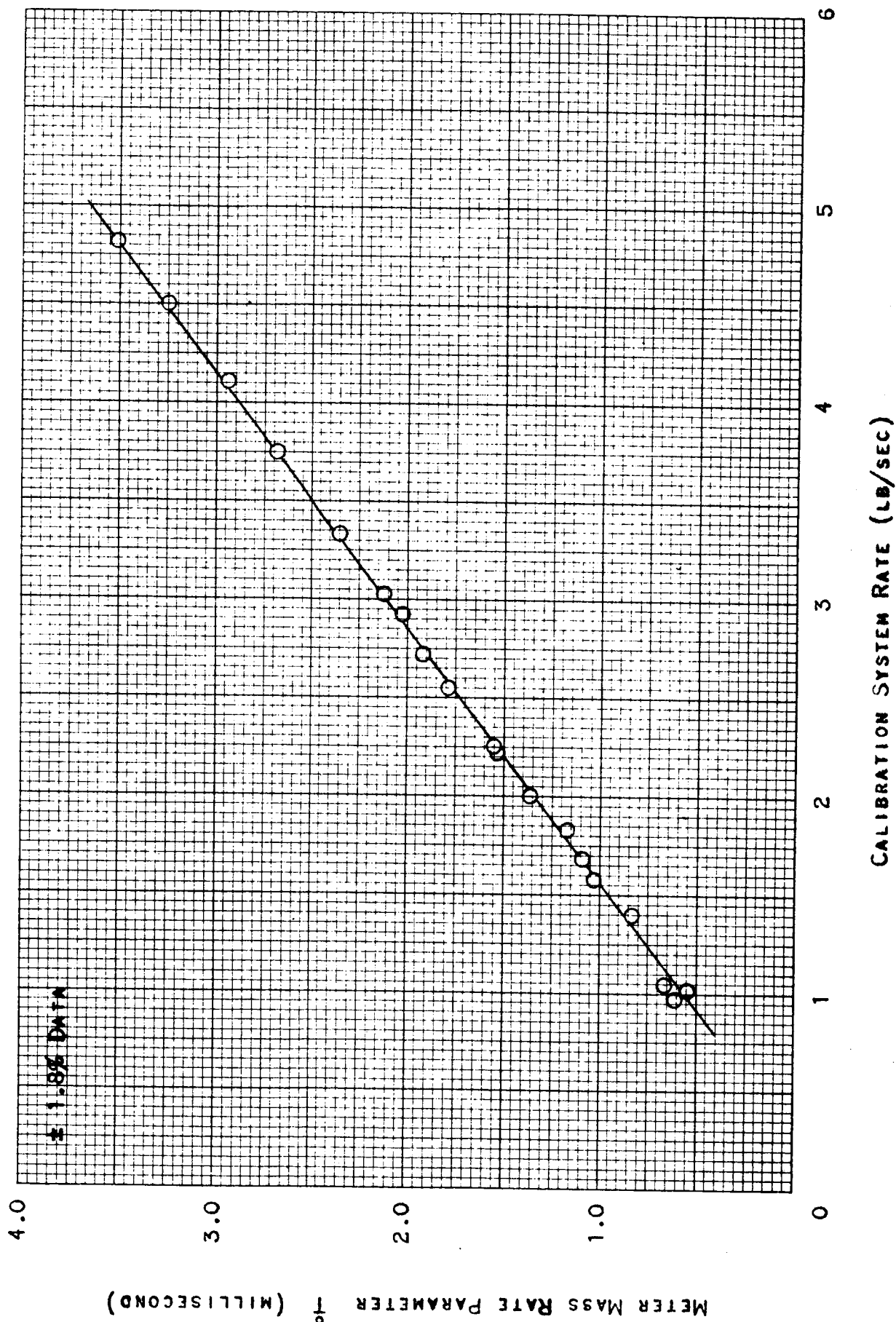


FIGURE 27

TABLE 9

POTTER TWIN TURBINE MASS FLOWMETER  
MODEL 1.5-3030, SERIAL PD-1.5-29  
LIQUID HYDROGEN CALIBRATION  
15, 16, 21 NOVEMBER 1962

Date and Point No.	Calibration System Rate (lb/sec)	---- Potter Mass Rate Parameter (millisec)	Mass Flowmeter----- Mass Constant (millisec/pps)	Volumetric Output (cycle/lb)	Backup Volumetric Output (cycle/lb)
15 Nov.					
1	3.214	---	---	23.835	135.310
2	4.164	---	---	23.764	135.270
3	4.162	---	---	23.779	135.310
4	4.142	---	---	23.744	135.130
5.	4.056	2.989	0.737	23.614	135.170
6	4.318	3.131	0.725	23.649	135.500
7	4.836	3.342	0.691	23.810	134.440
8	5.073	3.429	0.676	23.864	135.670
9	5.454	3.971	0.728	23.005	136.940
10	3.560	2.595	0.729	23.774	134.593
14	5.689	4.341	0.763	23.845	135.907
15	5.815	4.408	0.758	23.905	136.198
16	5.929	4.447	0.750	23.950	136.816
17	2.898	2,095	0,723	23,769	134,437
19	2.483	1.768	0.712	23.719	133.991

Note: The liquid hydrogen pressure and temperature at the flowmeter inlet was maintained at  $40 \pm 5$  psia and  $38.5 \pm 0.4^\circ\text{R}$ .

TABLE 9  
(Continued)

Date and Point No.	Calibration System Rate (lb/sec)	----- Potter Mass Flowmeter -----			Backup Volumetric Output (cycle/lb)
		Mass Rate Parameter (millisec)	Mass Constant (millisec/pps)	Volumetric Output (cycle/lb)	
16 Nov.					
1	4.050	2.997	0.740	23.694	135.080
2	4.061	2.993	0.737	23.594	134.613
3	4.062	2.977	0.733	23.539	134.518
4	4.058	2.974	0.733	23.564	134.648
5	4.056	2.969	0.732	23.513	134.528
6	4.910	3.624	0.738	23.689	134.548
7	5.002	3.681	0.736	23.649	134.402
8	5.758	4.324	0.751	23.799	135.882
9	5.405	3.821	0.707	23.865	136.289
10	4.430	3.114	0.703	23.659	135.772
11	5.385	3.823	0.710	23.810	136.028
12	5.419	3.896	0.719	23.850	135.857
13	2.152	1.511	0.702	23.539	133.569
21 Nov.					
1.	3.921	2.835	0.723	23.779	136.148
2	4.024	2.954	0.734	23.704	135.436
3	3.712	---	---	23.589	135.044
4	3.517	---	---	23.814	135.295

POTTER TWIN TURBINE MASS FLOWMETER

MODEL 1.5-3030, SERIAL PD-1.5-29

LIQUID HYDROGEN CALIBRATION

15, 16, 21 NOVEMBER 62

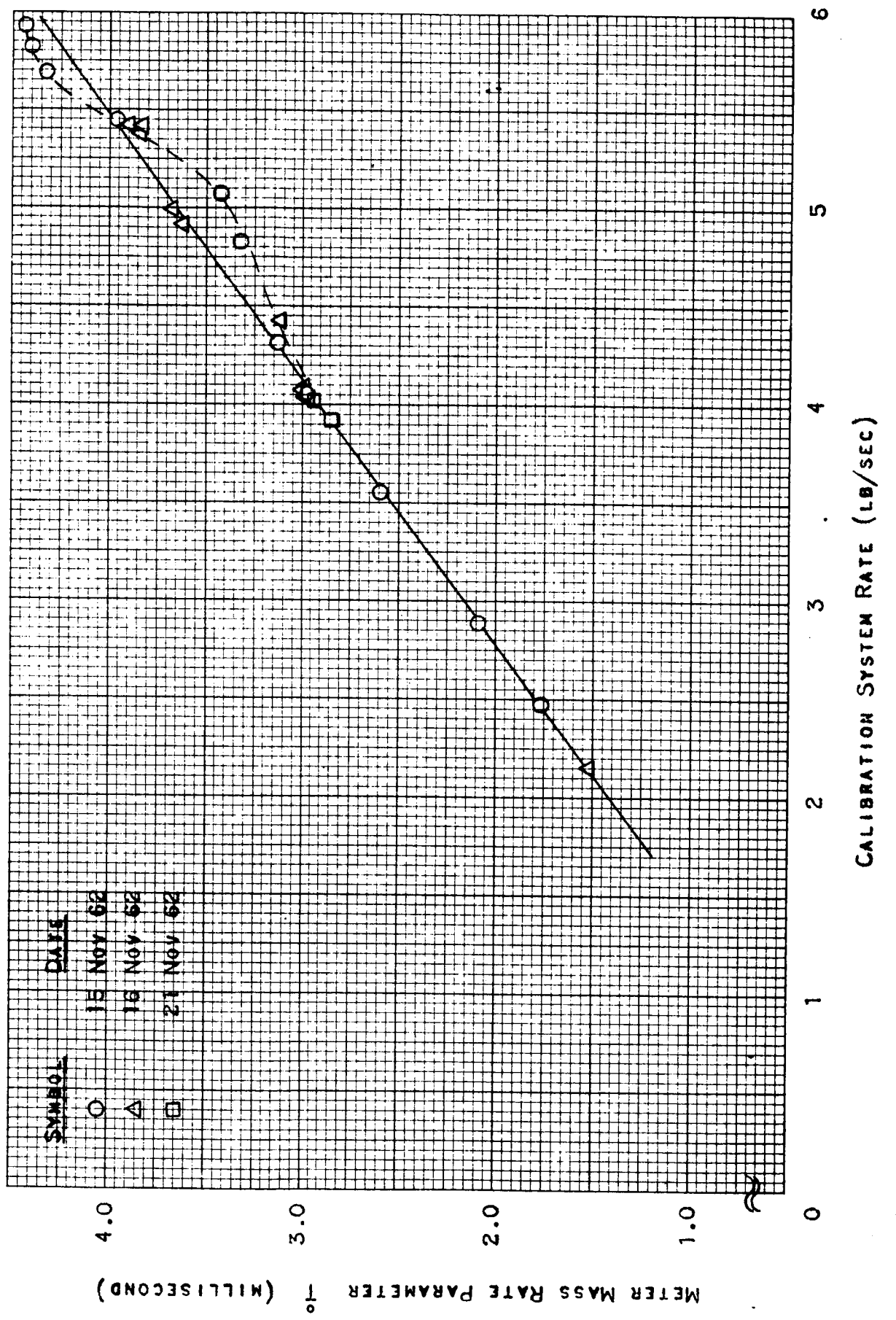


FIGURE 28

POTTER TWIN TURBINE MASS FLOWMETER

MODEL 1.5-3030, SERIAL PD-1.5-29

LIQUID HYDROGEN CALIBRATION

15, 16, 21 NOVEMBER 62

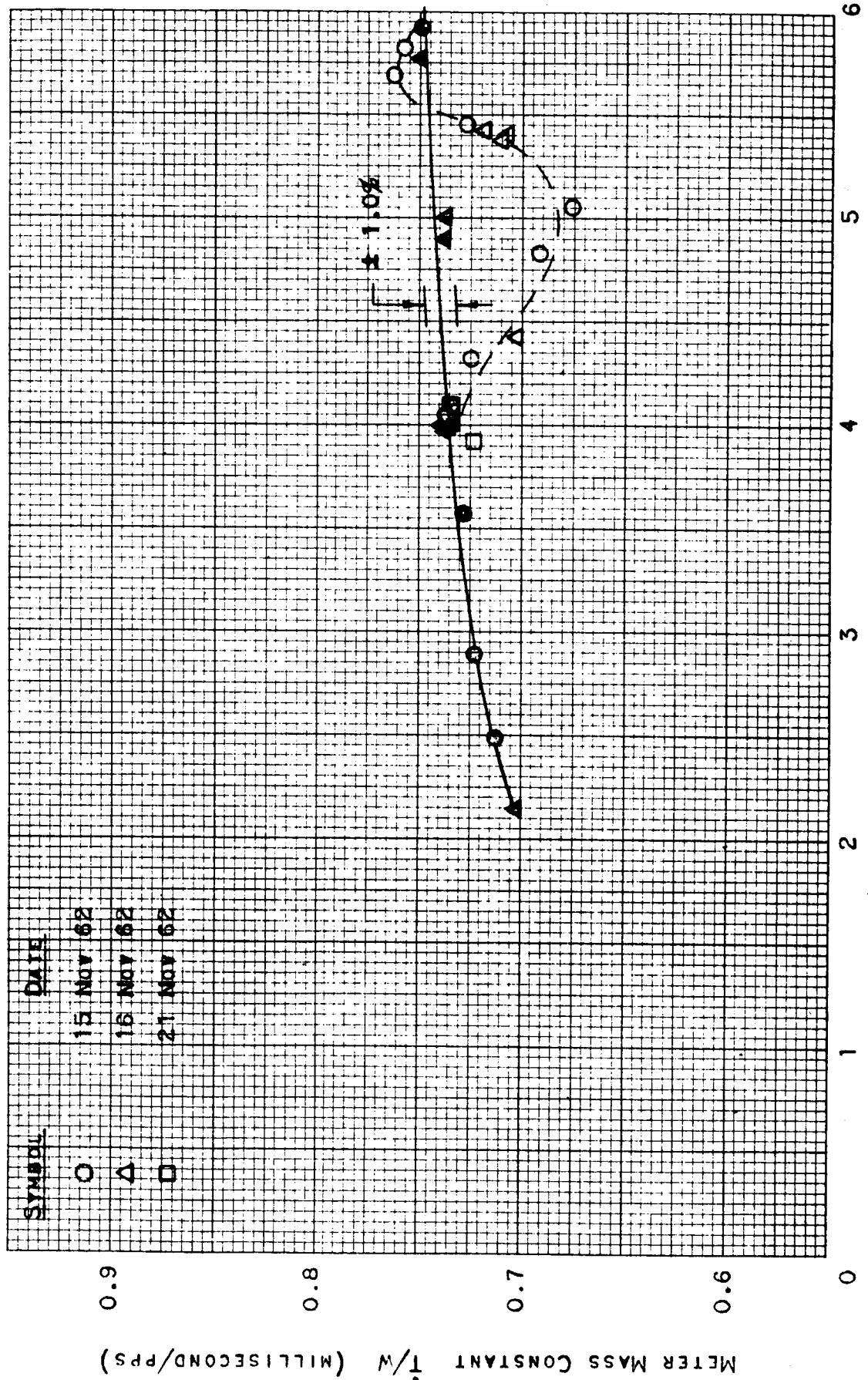


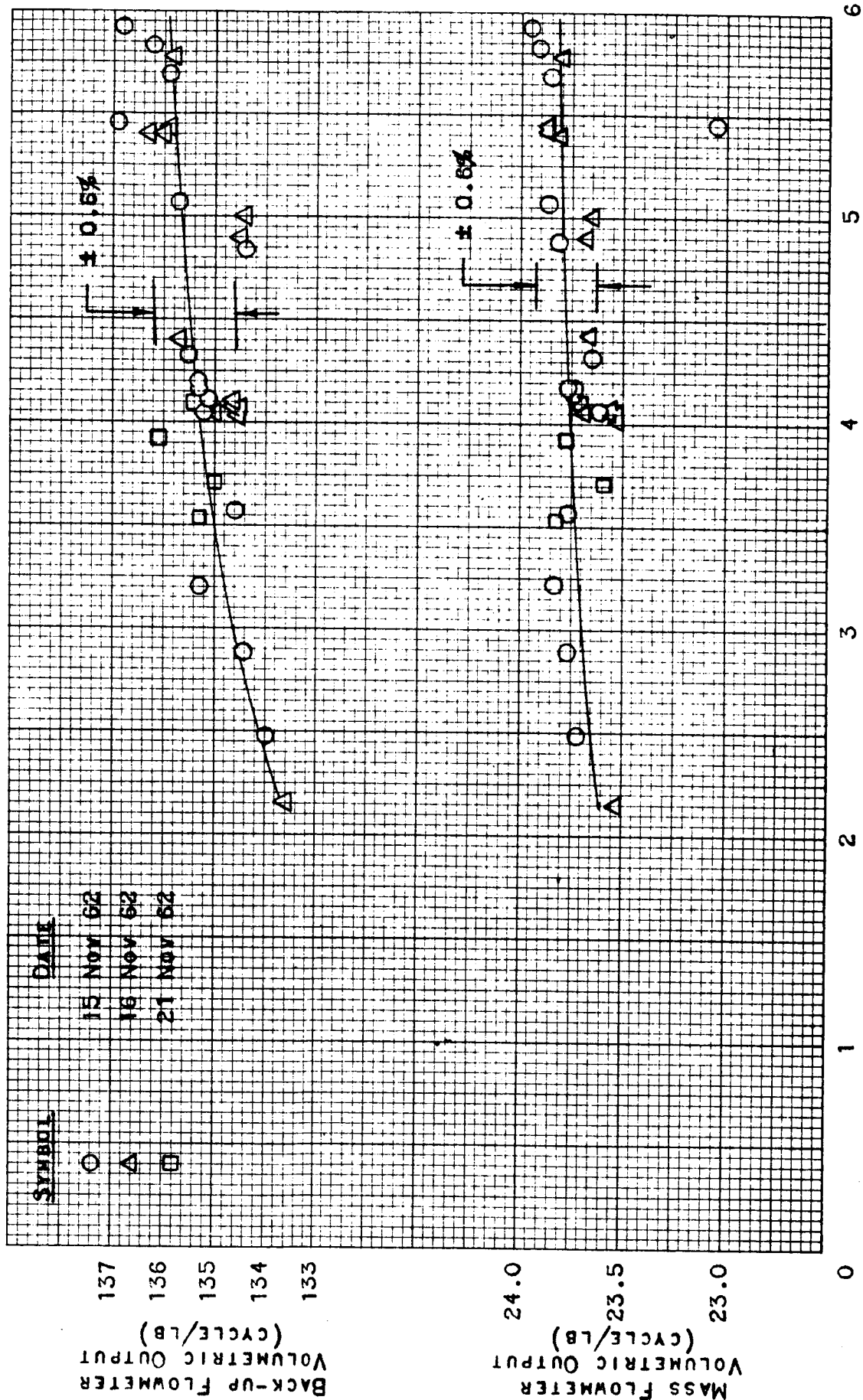
FIGURE 29

POTTER TWIN TURBINE MASS FLOWMETER

MODEL 1.5-3030, SERIAL PD-1.5-29

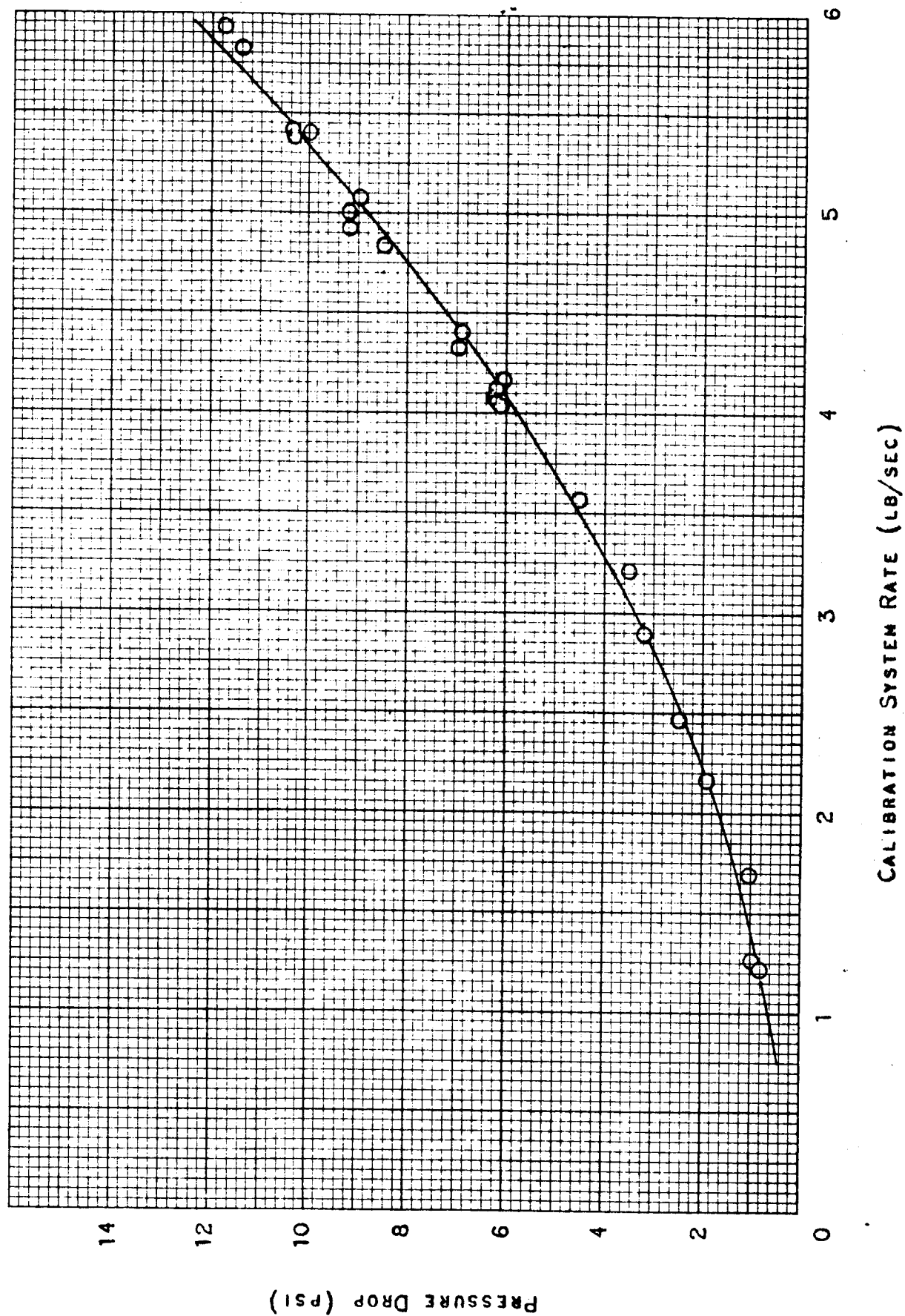
LIQUID HYDROGEN CALIBRATION

15, 16, 21 NOVEMBER 62





POTTER TWIN TURBINE MASS FLOWMETER  
MODEL 1.5-3030, SERIAL PD-1.5-29  
LIQUID HYDROGEN PRESSURE DROP CHARACTERISTICS



### Discussion of Test Data Obtained with the 3-Inch Flowmeter

The 3-inch Potter mass flowmeter was subjected to single-phase and two-phase calibrations with only minimal operational difficulties with the flowmeter and/or instrumentation equipment. The 3-inch flowmeter was calibrated using the instrumentation previously discussed for the 1-1/2 inch flowmeter.

On December 6, 1963, a 12 point calibration was performed which is presented in Table 10 and Figures 32 through 35. The flowmeter mass rate repeatability was within  $\pm 0.12\%$ . The improved accuracies and operational performance of the 3-inch flowmeter may be attributed to elimination of the original problems encountered with the 1-1/2 inch flowmeter.

On December 16, 1963, the flowmeter was subjected to two-phase calibration tests by injecting varying quantities of precooled helium upstream of the flowmeter. Prior to the performance of the two-phase test, initial single-phase calibration points were obtained to establish the single-phase performance of the flowmeter. The data obtained during the two-phase calibration test is presented in Table 11, and Figures 36 and 37.

An analysis of the data indicates that the flowmeter functions as a true mass flowmeter and is relatively insensitive to gas to liquid ratios up to 14%. Deviations in the mass flowmeter constant as a result of the varying gas to liquid ratio was random in nature, but remained less than 2% for gas to liquid ratio up to 14% (with the exception of two data points which deviated from the single-phase performance by 6%).

The effect of the two-phase flow on the volumetric output of the flowmeter is shown in Figure 37.

TABLE 10

POTTER TWIN TURBINE MASS FLOWMETER  
MODEL 3-3054, SERIAL RAA-3-10  
LIQUID HYDROGEN CALIBRATION  
6 DECEMBER 1963

Point No.	Calibration System Rate (lb/sec)	Mass Rate Parameter (millisec)	Mass Constant (millisec/pps)	Volumetric Output (cycle/lb)
1	6.988	3.770	0.5395	30.984
2	7.708	4.192	0.5439	31.013
3	8.942	4.955	0.5541	31.003
4	10.201	5.719	0.5606	31.064
5	10.760	6.038	0.5612	31.094
6	12.120	6.755	0.5582	31.042
7	6.240	3.269	0.5239	31.000
8	5.045	2.604	0.5162	31.000
9	3.946	1.912	0.4845	30.950
10	3.042	1.363	0.4481	30.857
11	2.227	0.918	0.4122	30.704
12	1.024	---	---	30.576

Note: The liquid hydrogen pressure and temperature at the flowmeter inlet was maintained at  $45 \pm 5$  psia and  $38.5 \pm 0.4^{\circ}\text{R}$ .

POTTER TWIN TURBINE MASS FLOWMETER

MODEL 3-3054, SERIAL RAA-3-10

LIQUID HYDROGEN CALIBRATION

6 DECEMBER 63

FIGURE 32

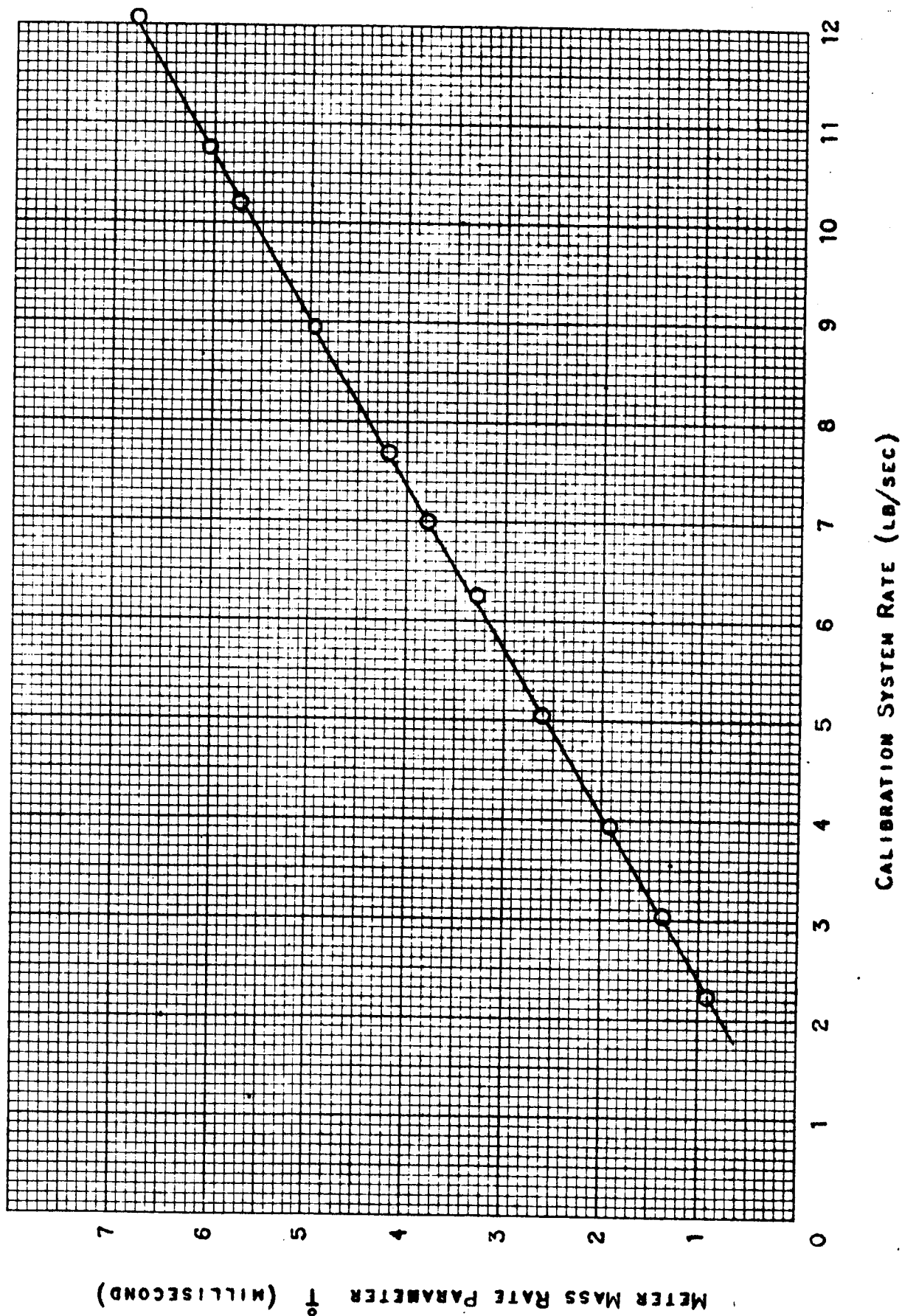


FIGURE 33

POTTER TWIN TURBINE MASS FLOWMETER

MODEL 3-3054, SERIAL RAA-3-10

LIQUID HYDROGEN CALIBRATION

6 DECEMBER 63

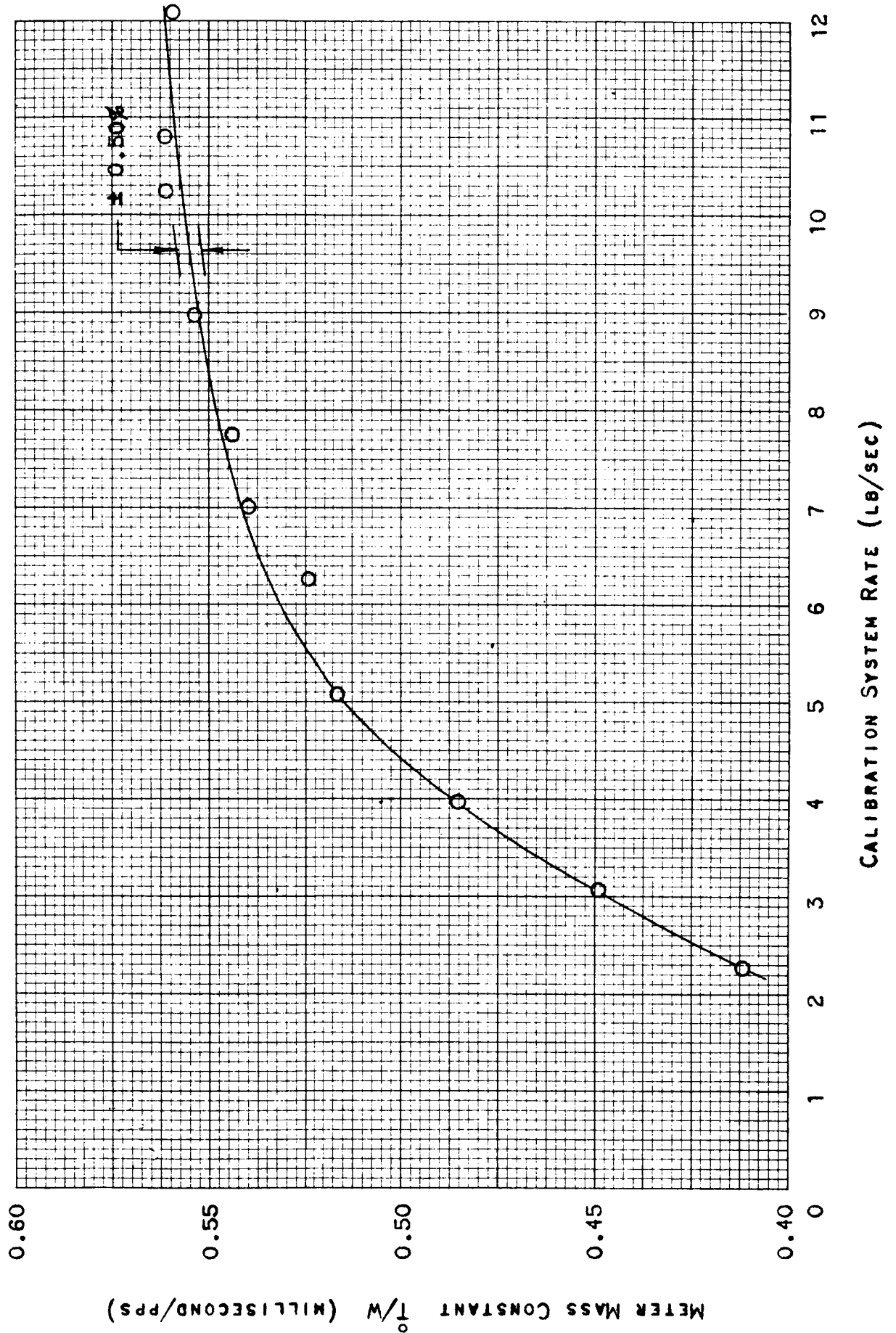


FIGURE 34

POTTER TWIN TURBINE MASS FLOWMETER

MODEL 3-3054, SERIAL RAA-3-10

LIQUID HYDROGEN CALIBRATION

6 DECEMBER 63

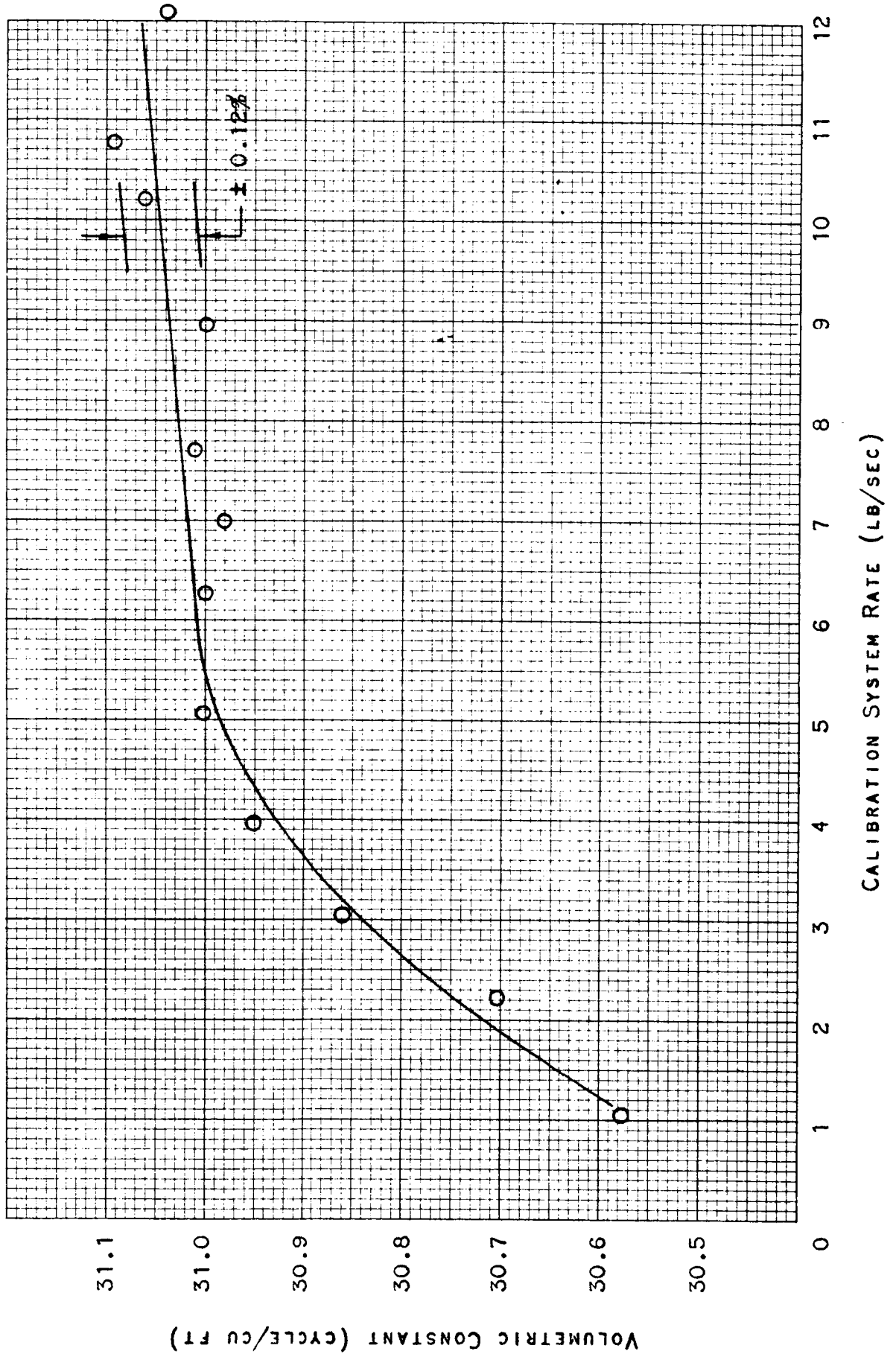


FIGURE 35

POTTER TWIN TURBINE MASS FLOWMETER  
MODEL 3-3054, SERIAL RAA-3-10  
LIQUID HYDROGEN PRESSURE DROP CHARACTERISTICS

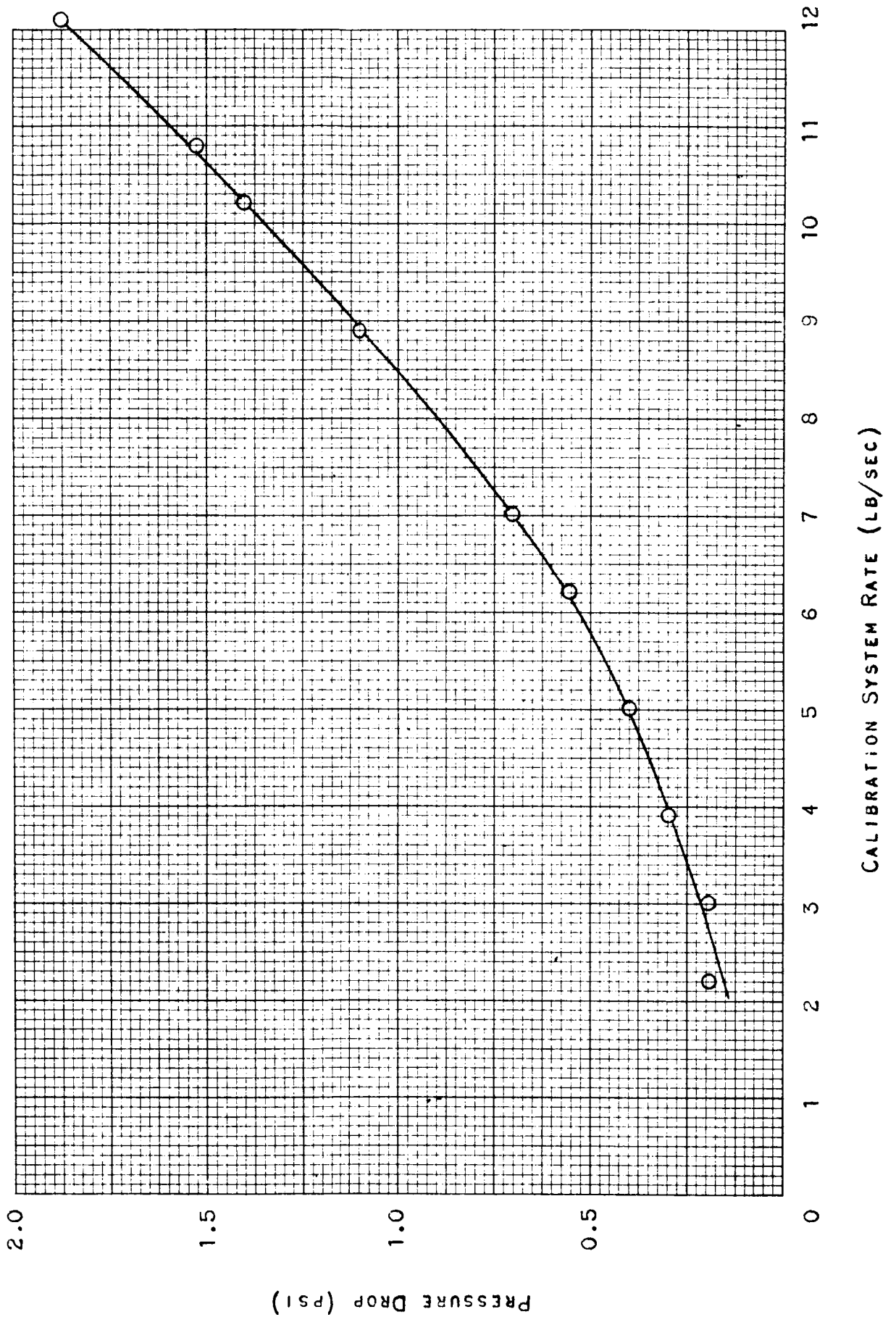


TABLE 11

POTTER TWIN TURBINE MASS FLOWMETER  
MODEL 3-3054, SERIAL RAA-3-10  
LIQUID HYDROGEN - GASEOUS HELIUM - DUAL PHASE  
CALIBRATIONS  
16 DECEMBER 1963

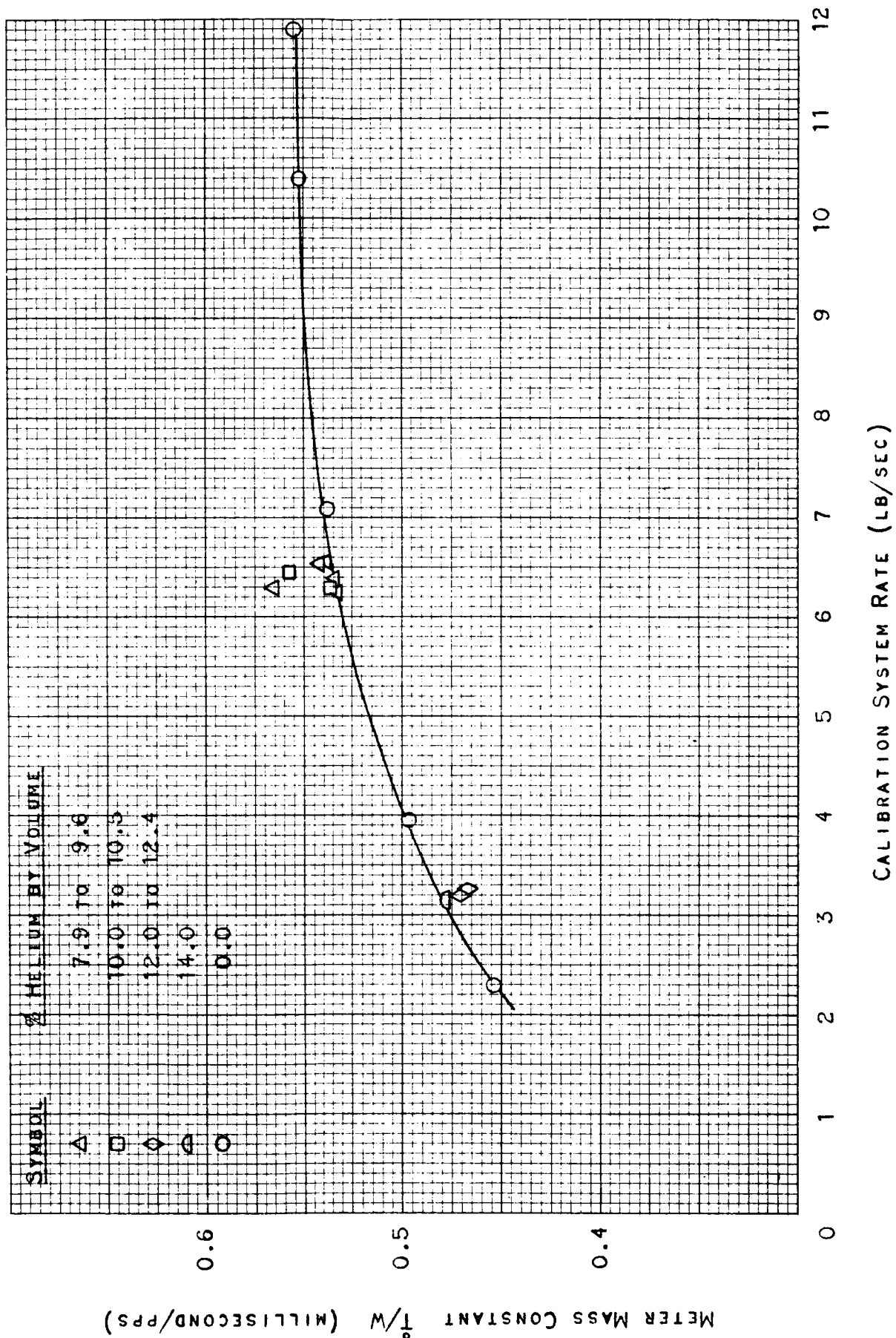
Point No.	System Rate (lb/sec)	Mass Rate Parameter (millisec)	Mass Constant (millisec/pps)	Volumetric Output (cycle/lb)	Gas to Liquid Ratio (% by Vol.)
1	10.51	5.802	0.5519	7.167	--
2	2.300	1.045	0.4543	7.077	--
3	3.219	1.512	0.4697	7.990	12.1
4	3.255	1.519	0.4666	7.990	12.4
5	3.154	1.506	0.4776	8.146	14.0
6	6.469	3.612	0.5583	7.428	10.2
7	6.321	3.325	0.5260	7.569	9.6
8	6.253	3.335	0.5333	7.594	9.7
9	6.297	3.361	0.5336	7.564	10.5
10	6.396	3.417	0.5342	7.488	9.0
11	6.558	3.548	0.5411	7.423	7.9
12	6.554	3.529	0.5385	7.433	7.9
13	7.108	3.825	0.5382	7.167	--
14	3.950	1.959	0.4960	7.132	--
15	11.92	6.623	0.5556	7.167	---

Note: The liquid hydrogen pressure and temperature at the flowmeter inlet was maintained at  $45 \pm 5$  psia and  $38.5 \pm 0.4^{\circ}\text{R}$ .



POTTER TWIN TURBINE MASS FLOWMETER  
 MODEL 3-3054, SERIAL RAA-3-10  
 LIQUID HYDROGEN-GASEOUS HELIUM DUAL PHASE CALIBRATION

16 DECEMBER 63



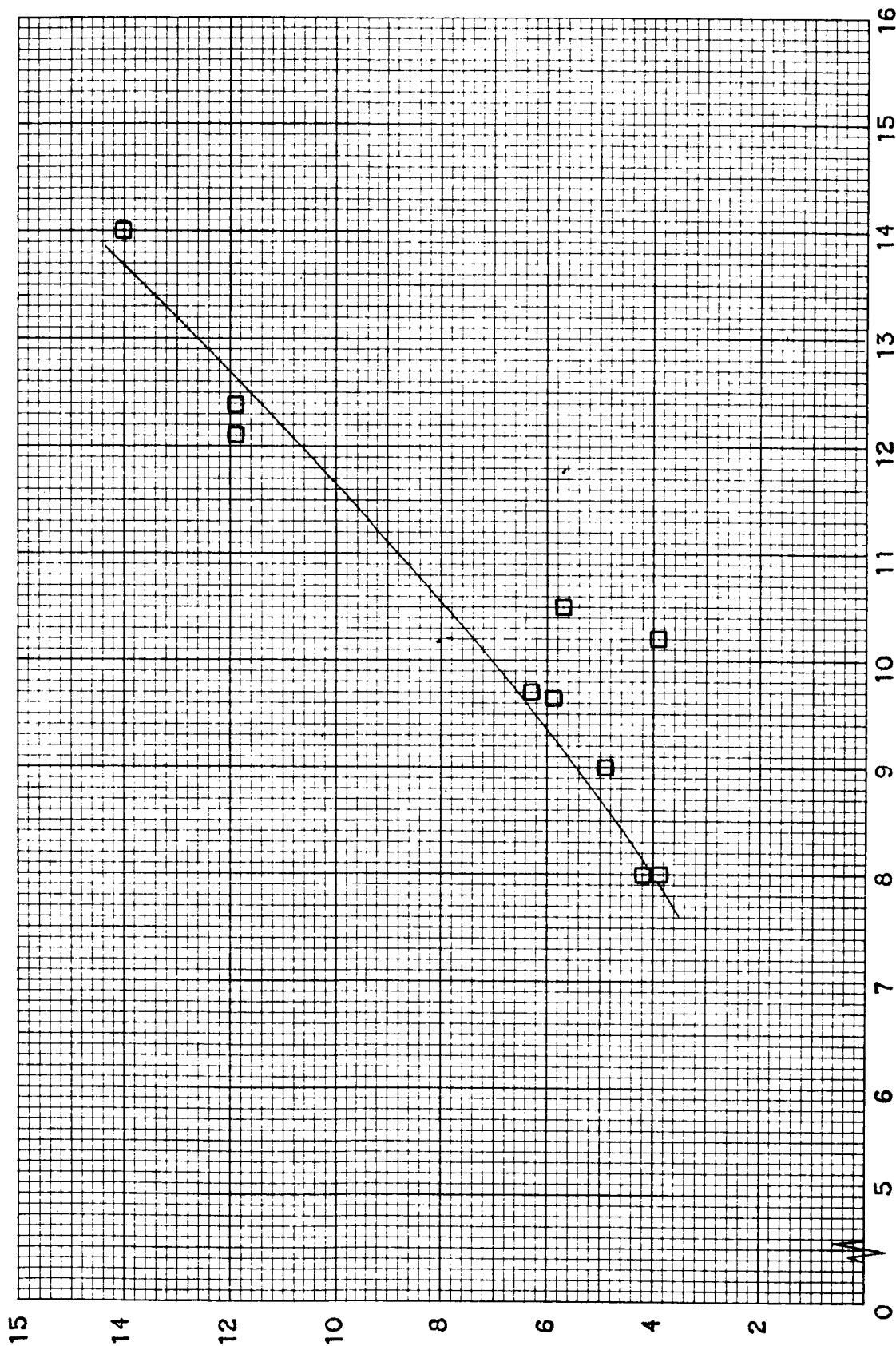
POTTER TWIN TURBINE MASS FLOWMETER

MODEL 3-3054, SERIAL RAA-3-10

LIQUID HYDROGEN-GASEOUS HELIUM DUAL PHASE CALIBRATION

16 DECEMBER 63

FLOWMETER DEVIATION FROM SINGLE PHASE VOLUMETRIC CONSTANT (%)



CALCULATED FLUID QUALITY (% BY VOLUME)

FIGURE 37

## EVALUATION OF THE WAUGH ENGINEERING COMPANY AXIAL MOMENTUM MASS FLOWMETER

### Description

The Waugh mass flowmeter operates on an application of the momentum principle. In this application, a turbine, driven by a constant torque power source, imparts angular momentum to the fluid. Under these conditions the mass flow rate through the system is equal to the torque input to the turbine divided by the angular velocity of the turbine. Since the torque input is constant, the mass flow rate becomes inversely proportional to the angular velocity of the turbine. The constant torque input is achieved with a magnetic hysteresis drive which is independent of rotational speed and very nearly independent of temperature. A conventional magnetic pick-up coil mounted adjacent to the turbine rotor generates the flowmeter output signal. This ac signal, which is proportional to the rotor speed is, therefore, inversely proportional to the mass flow rate. The period of the generated signal is directly proportional to the mass flow rate and may be indicated digitally by conventional time interval counters.

The flowmeter housing with a vacuum jacketed configuration, and the annular flow passage with anti-swirl veins are shown in Figures 38 and 39. The installation of the flowmeter is shown in Figure 40.

Advantages of the Waugh mass flowmeter system may be summarized as follows:

1. Flow through the flowmeter is axial with a subsequently low pressure loss.
2. The turbine rotation is inversely proportional to mass flow rate thus precluding the possibility of overspeed conditions.
3. The output signal is in direct digital form, requiring no complex secondary electronics.
4. The design is relatively simple with a single primary rotating component.

A potential disadvantage of the Waugh mass flowmeter system arises in the use of a motor driven turbine which requires that external power be supplied to the flowmeter.

THE WAUGH AXIAL MOMENTUM MASS FLOWMETER MODEL FM-48-400

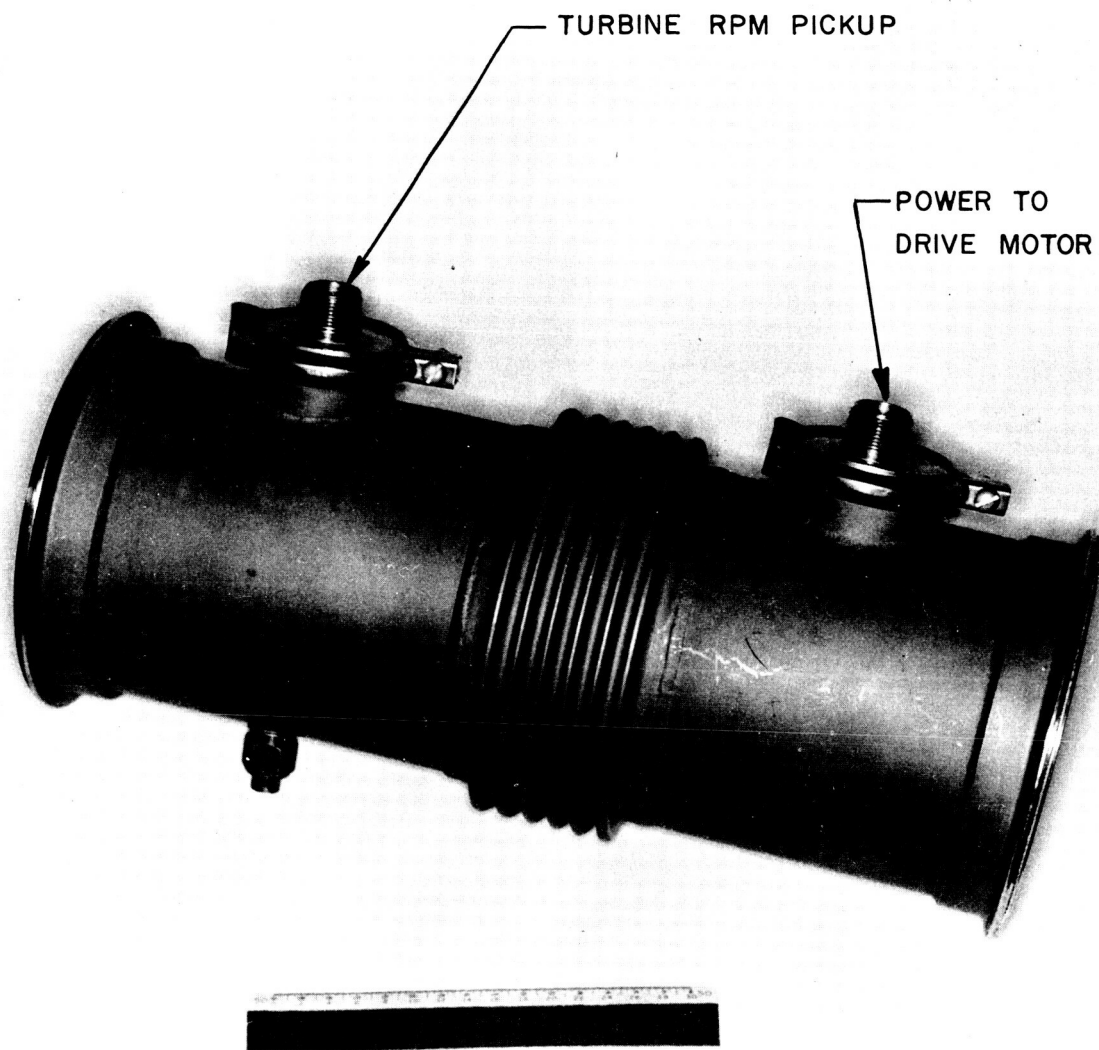
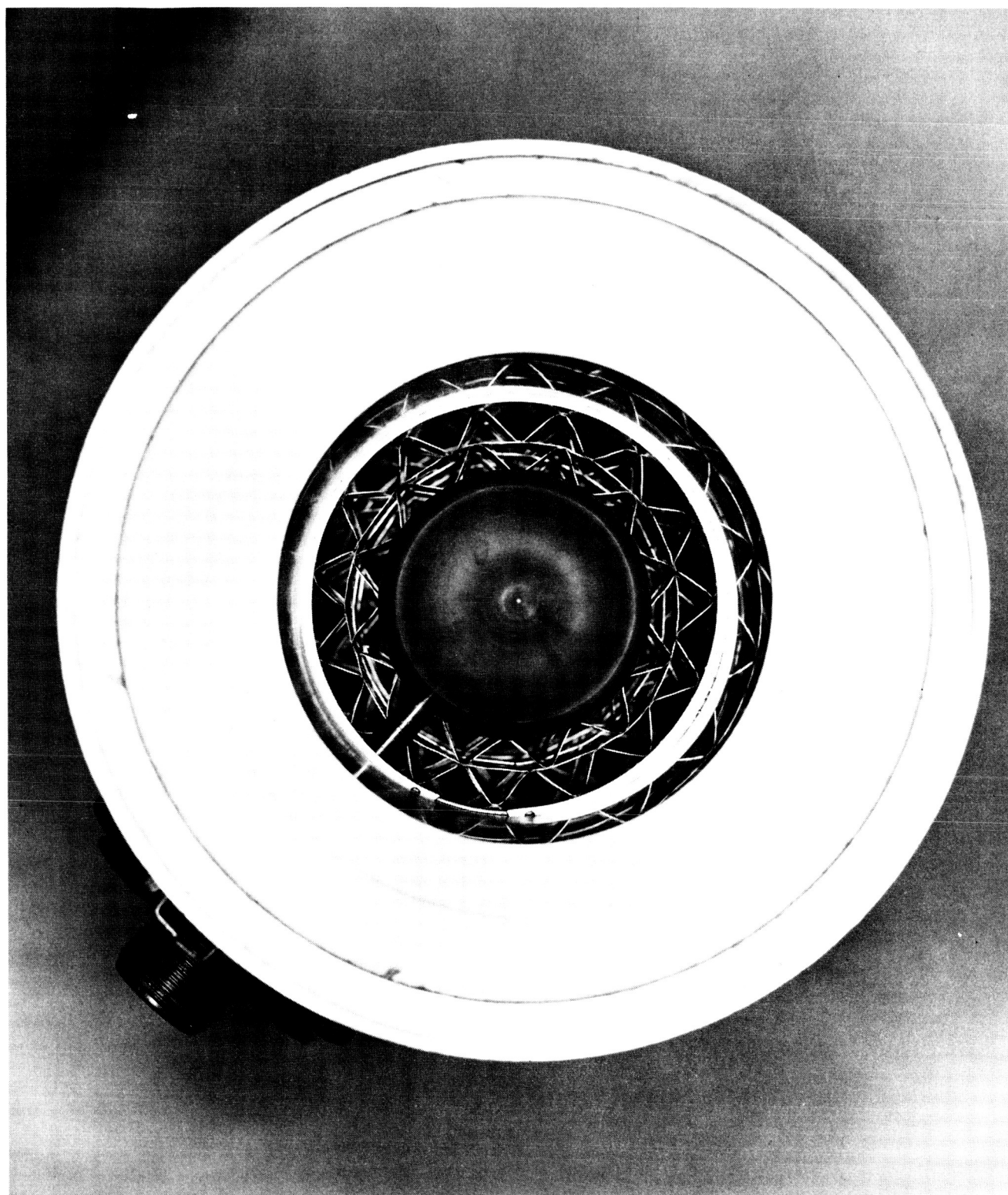


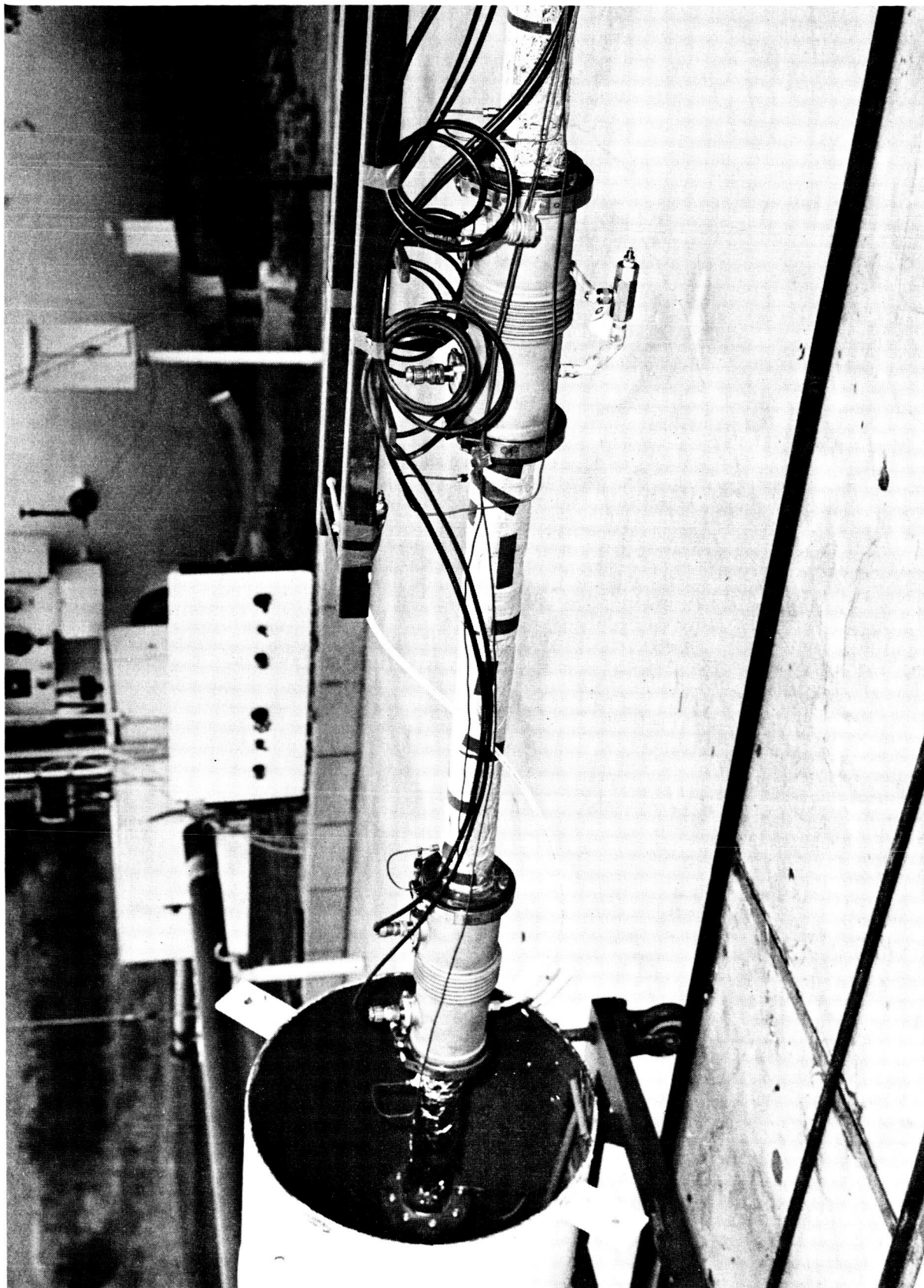
FIGURE 38



ANNULAR FLOW PASSAGE AND ANTI-SWIRL GRID IN THE  
FLOWMETER INLET

FIGURE 39





TANDEM CALIBRATION OF FLOWMETERS S/N 16162 AND S/N 16164

FIGURE 40

A series of tests was conducted July 30 and August 3 with Serial Numbers 16162 and 16164 installed in the system simultaneously. Data points were obtained with the upstream flowmeter operating in both the clockwise and counter-clockwise direction to detect the presence of a swirl setup by the upstream flowmeter which would affect the calibration of the downstream flowmeter. On July 30 data points 1 through 12 were obtained with the upstream flowmeter (S/N 16162) rotating clockwise with the data points 13 through 19 obtained with the upstream flowmeter (S/N 16162) rotating counter-clockwise.

The clockwise data for flowmeter S/N 16162 was erratic and is not included in Table 16 or Figure 47. The data for flowmeter S/N 16164 shown in Figure 47 indicates that the flowmeter performance was unaffected by the direction of rotation of the upstream flowmeter.

Modification of the flowmeter drive motors was found to be necessary as a result of the failure of the motors in Serial Numbers 16162 and 16163 while undergoing water calibration at the manufacturer's facility. The motor design was determined to be suitable for operation in liquid hydrogen with a dielectric constant of approximately 1.23, but was subject to overheating in water with a dielectric constant of 80.4. The motor modification consisted of totally enclosing the motor windings in sealed units to eliminate contact with the test medium.

In addition to enclosing the drive motors, flowmeters Serial Numbers 16162 and 16163 were further modified by reducing the number of magnetic elements on the circumference of the turbine assembly from 60 elements to 30. This reduced the effective output frequency of any given flow rate by a factor of two, subsequently increasing the effective period or mass rate parameter by a factor of two.

Tandem calibrations were conducted February 6 and 7, 1963 with Serial Number 16164 upstream, and Serial Number 16163 downstream. On February 20, 1963, additional calibrations were performed with Serial Number 16162 upstream and Serial Number 16164 downstream. The data obtained during these calibrations are presented in Tables 17 through 20. During these calibrations, a shift in performance was observed when flowmeter Serial Number 16164 was moved from the upstream line position of February 6 and 7, to the downstream line position of February 20. This data is presented in Figure 48. The exact cause of the data shift was not determined; however, it was felt that the flowmeter was more sensitive to inlet conditions than had been presumed, and that the upstream flowmeter removed any fluid swirl produced by the calibration system.

## Discussion of the Test Data Obtained with the Waugh Axial Momentum Mass Flowmeter

During the program, four identical flowmeters were evaluated. The results of this work are presented in a chronological sequence.

Preliminary calibration work with the Waugh mass flowmeter system was performed in May, 1962 utilizing flowmeter Serial Number 16162. During these calibrations, a data shift occurred between the data obtained May 22, 23, and 24 and the data obtained on May 28 and 29. The evaluation of the latter data indicated that a trimming problem existed in either the flowmeter's turbine assembly or upstream flow straighteners. The existence of a non-zero blade angle relative to the axis of the flow of the fluid will produce a rotational torque which will either increase or decrease the net torque input and subsequently shift the mass rate output. The data obtained during these initial calibrations is presented in Table 12, and Figures 41 and 42. Flowmeter, Serial Number 16162, was subsequently returned to the manufacturer for trimming in their water calibration system.

The second meter to be evaluated was Serial Number 16161. As a result of the trimming problems encountered with Serial Number 16162, the second unit was calibrated with the turbine driven in both the clockwise and counter-clockwise directions. These tests were performed May 25 and 31, and June 4, 1962, and are summarized in Table 13 and Figures 43 and 44. This data shows conclusively the effect of the flowmeter's rotational direction and the degree of trimming, upon the calibration data.

In June, 1962, calibration tests were performed with flowmeter, Serial Number 16164, during which the turbine was operated in both the clockwise and counter-clockwise directions to evaluate the relative trimming of the flowmeter. Prior to submitting this flowmeter for evaluation, the manufacturer performed a series of tests in their water calibration stand, specifically intended to optimize the flowmeter's trim condition.

The data presented in Table 14 and Figures 45 and 46 demonstrates the ideal characteristics of this type of flowmeter in that no significant change in the flowmeter's performance is detected as a result of the direction of rotation of the turbine. The flowmeter also demonstrated the capability to provide mass flow rate measurements to within approximately  $\pm 0.5\%$ .



Variable density tests were conducted August 1 and 3, 1962 with flowmeter, Serial Number 16164 upstream and flowmeter, Serial Number 16162 downstream. These tests were performed using the helium injection techniques previously described. Volumetric helium to hydrogen ratios were achieved up to approximately 12% over a flow range of 4.5 through 5.2 pps. The data obtained during these tests is presented in Table 21 and Figure 49.

The mass constant for each flowmeter was shifted approximately 1% from the single phase data obtained July 30 and August 3 with a scatter of approximately  $\pm 1\%$  for gas to liquid ratios up to 12%. Since this reduction in the flowmeter constant was the same for both flowmeters, and the fact that there is no apparent consistency in the data scatter with respect to the volumetric percentage of helium introduced in the system, it is felt that the data shift was a function of the operation of the variable density system. The specific characteristic of the system which would cause this shift has not been determined, however, in performing the variable density tests, there is one flexible hose which carries the gas off the calibration stand which is pressurized during the calibration run. Under normal single phase calibrations, this hose is not pressurized.

The liquid hydrogen pressure characteristics of the Waugh axial momentum mass flowmeter, Model FM-48-400 are presented in Figure 50.

TABLE 12

WAUGH AXIAL MOMENTUM MASS FLOWMETER  
MODEL FM-48-400, SERIAL NUMBER 16162  
LIQUID HYDROGEN CALIBRATION  
22, 23, 24, 28, and 29 MAY 1962

Date	Point No.	System Rate (lb/sec)	Mass Rate Parameter (1/cps)	Mass Constant (1/cps·pps)
22 May	1	3.499	$6.106 \times 10^{-3}$	$1.745 \times 10^{-3}$
Counter- Clockwise	2	3.473	6.032	1.746
	3	3.005	5.312	1.768
	4	2.803	4.984	1.778
	5	1.874	3.389	1.808
	6	0.735	1.354	1.842
	7	1.707	3.096	1.814
23 May	1	3.840	$7.024 \times 10^{-3}$	$1.829 \times 10^{-3}$
Counter- Clockwise	2	3.984	7.373	1.851
	3	4.183	7.747	1.852
	4	4.185	7.681	1.835
	5	4.538	8.190	1.805
	6	4.806	8.457	1.760
	8	5.138	8.889	1.730
	9	3.724	6.895	1.852
	10	3.654	6.842	1.872
	11	3.446	6.441	1.869
	12	3.213	6.035	1.878
	13	2.868	5.416	1.888
	14	2.641	4.995	1.891
	15	2.398	4.547	1.896
	16	2.136	4.058	1.900
	17	1.860	3.547	1.907

Note: The flowmeter inlet conditions were maintained at  $45 \pm 5$  psia and  $38 \pm 0.5^\circ\text{R}$ .

TABLE 12  
(Continued)

Date	Point No.	System Rate (lb/sec)	Mass Rate Parameter (1/cps)	Mass Constant (1/cps · pps)
23 May (Cont. )	18	1. 539	2. 951	1. 917
	19	1. 136	2. 201	1. 938
	20	0. 747	1. 460	1. 954
	21	0. 493	0. 942	1. 911
24 May Counter- Clockwise	1	0. 493	$0. 853 \times 10^{-3}$	$1. 730 \times 10^{-3}$
	2	0. 748	1. 336	1. 786
	3	1. 144	2. 048	1. 790
	4	1. 487	2. 632	1. 770
	5	1. 833	3. 239	1. 767
	6	2. 129	3. 743	1. 758
	7	2. 358	4. 121	1. 748
	8	2. 553	4. 457	1. 746
	9	2. 753	4. 760	1. 729
	10	3. 140	5. 408	1. 722
	12	3. 383	5. 561	1. 644
	13	3. 569	5. 992	1. 679
	14	3. 647	6. 099	1. 672
	15	3. 970	6. 570	1. 655
	16	4. 292	6. 999	1. 631
	17	4. 539	7. 412	1. 633
	18	4. 925	7. 813	1. 586
	19	5. 059	7. 987	1. 579
	20	5. 771	8. 735	1. 514
	21	6. 863	10. 564	1. 539

TABLE 12  
( Continued)

Date	Point No.	System Rate (lb/sec)	Mass Rate Parameter (1/cps)	Mass Constant (1/cps·pps)
28 May	1	0.549	$1.062 \times 10^{-3}$	$1.934 \times 10^{-3}$
Counter- Clockwise	2	0.737	1.427	1.947
	3	1.153	2.183	1.893
	4	1.517	2.895	1.908
	5	1.793	3.405	1.899
	6	1.979	3.750	1.895
	7	2.172	4.113	1.894
	8	2.351	4.512	1.919
	9	2.487	4.756	1.912
	10	2.742	5.232	1.908
	11	2.876	5.477	1.904
	12	2.928	5.575	1.904
	13	3.238	6.159	1.902
	14	3.249	6.165	1.898
	15	3.582	6.668	1.861
	16	3.817	6.838	1.791
	17	4.075	7.160	1.757
	18	4.220	7.321	1.735
	19	5.125	8.602	1.678
	20	4.817	8.193	1.701
	22	2.102	4.001	1.903
	24	3.565	6.534	1.833
	25	3.949	7.137	1.807

TABLE 12  
(Continued)

Date	Point No.	System Rate (lb/sec)	Mass Rate Parameter (1/cps)	Mass Constant (1/cps·pps)
29 May	1	0.650	$1.262 \times 10^{-3}$	$1.942 \times 10^{-3}$
Counter- Clockwise	2	0.786	1.534	1.952
	3	0.897	1.747	1.948
	4	1.344	2.578	1.918
	5	1.807	3.430	1.898
	6	2.196	4.130	1.881
	7	2.542	4.731	1.861
	8	2.837	5.233	1.845
	9	3.103	5.662	1.825
	10	3.360	6.074	1.808
	11	3.698	6.560	1.774
	12	4.026	6.986	1.735
	13	4.290	7.331	1.709
	14	4.475	7.546	1.686
	15	4.563	7.648	1.676
	16	4.725	7.801	1.651
	18	1.342	2.565	1.911
	19	2.168	4.075	1.879
	20	2.862	5.228	1.827

FIGURE 41

WAUGH AXIAL MOMENTUM MASS FLOWMETER

MODEL FM-48-400, SERIAL 16162

LIQUID HYDROGEN CALIBRATION

29 MAY 62

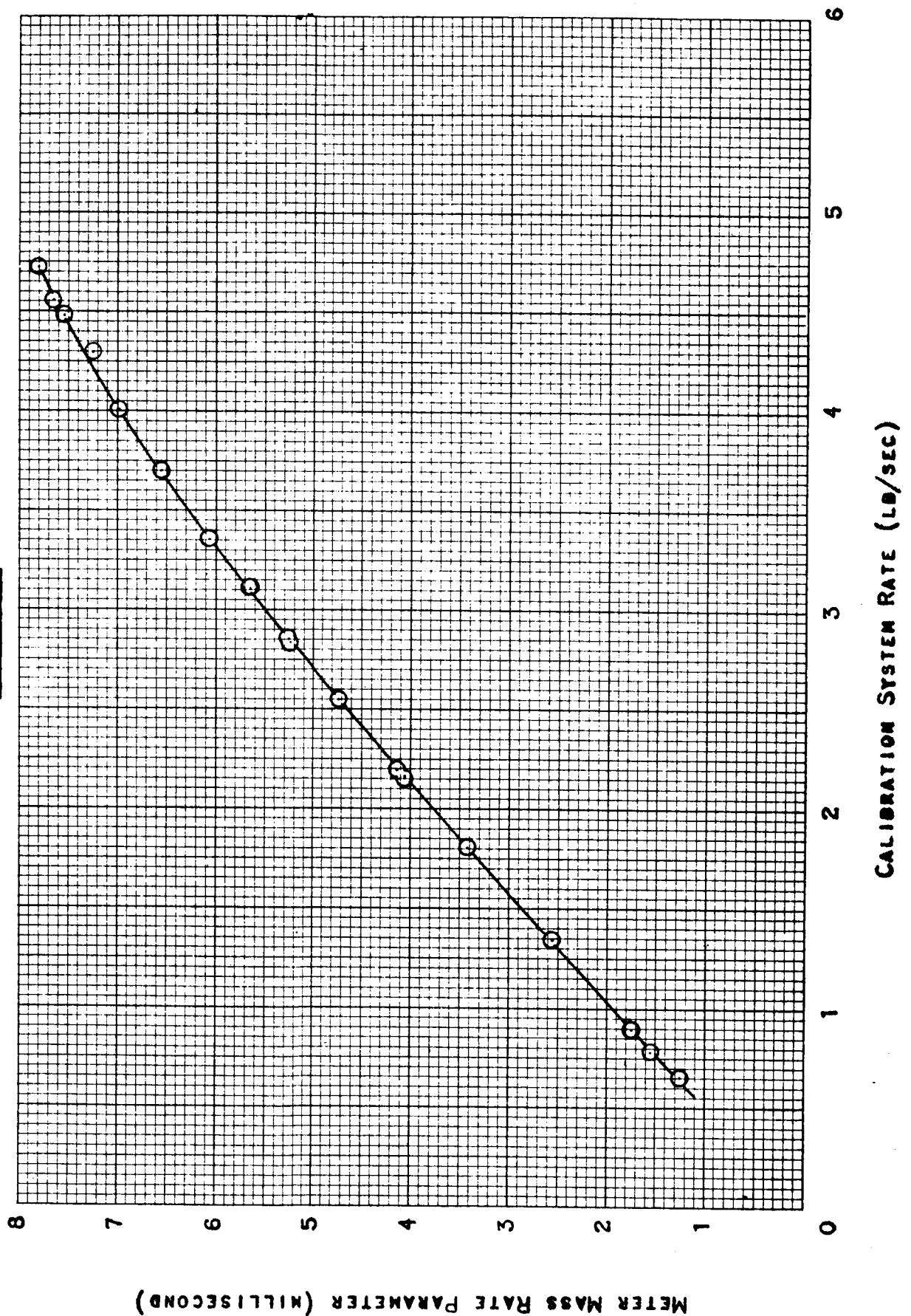


FIGURE 42

WAUGH AXIAL MOMENTUM MASS FLOWMETER

MODEL FM-48-400, SERIAL 16162

LIQUID HYDROGEN CALIBRATION

29 MAY 62

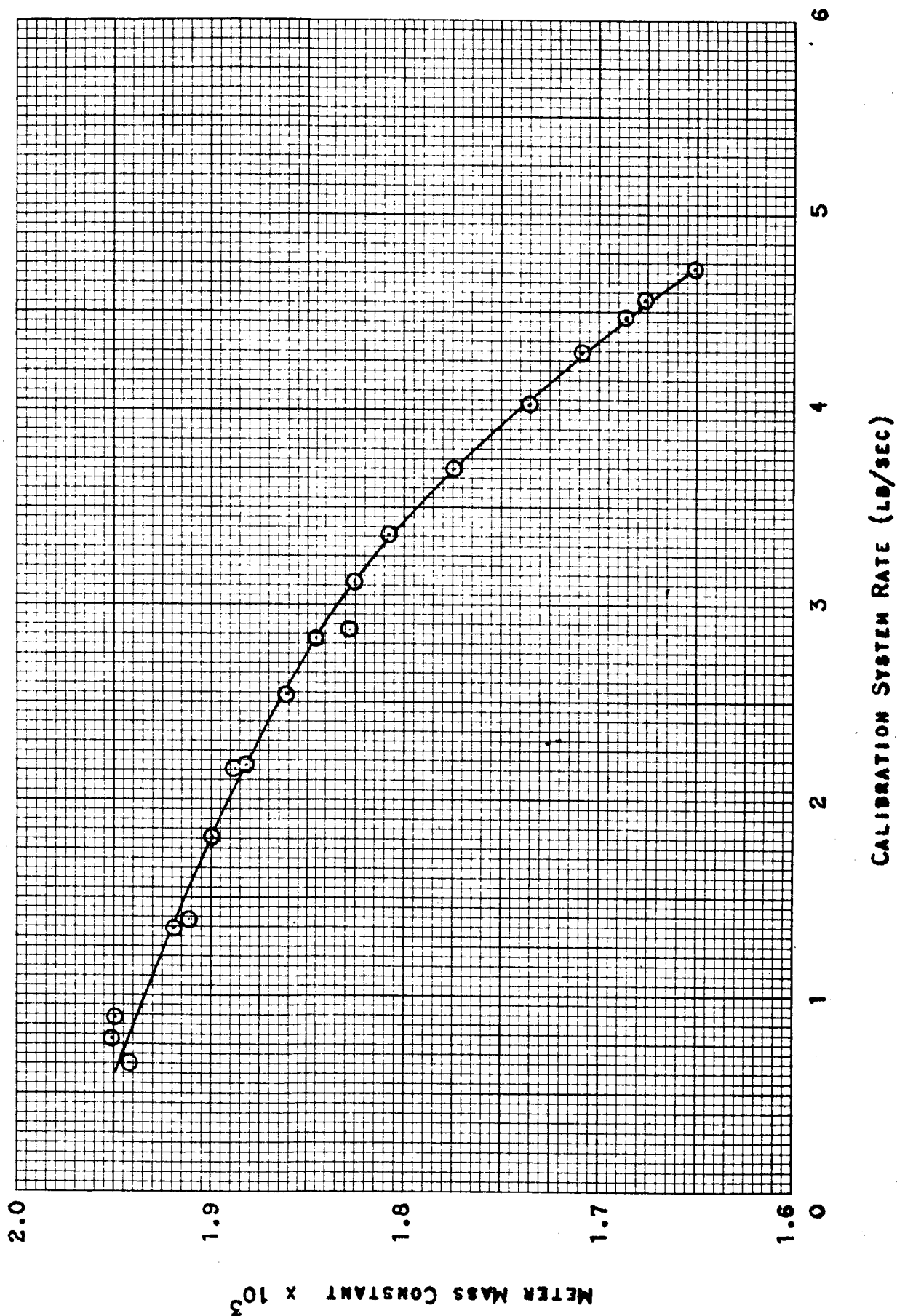


TABLE 13

WAUGH AXIAL MOMENTUM MASS FLOWMETER  
MODEL FM-48-400, SERIAL 16161  
LIQUID HYDROGEN CALIBRATION  
25, 31 MAY AND 4 JUNE 1962

Date	Point No.	System Rate (lb/sec)	Mass Rate Parameter (1/cps)	Mass Constant (1/cps · pps)
25 May	1	1.851	$3.474 \times 10^{-3}$	$1.877 \times 10^{-3}$
Counter- Clockwise	2	2.818	5.332	1.892
	3	3.380	6.474	1.915
	4	3.626	7.006	1.932
	5	4.305	8.453	1.964
	6	4.878	10.300	2.112
	7	0.604	1.129	1.869
31 May	1	0.495	$0.915 \times 10^{-3}$	$1.848 \times 10^{-3}$
Counter- Clockwise	2	0.907	1.710	1.885
	3	1.337	2.486	1.859
	4	1.855	3.444	1.857
	5	2.562	4.778	1.865
	6	2.933	5.475	1.867
	7	3.496	6.513	1.863
	8	4.045	7.483	1.850
	9	4.391	8.322	1.895
	10	4.980	10.517	2.112

Note: Flowmeter inlet conditions were maintained at  $45 \pm 5$  psia,  
and  $38 \pm 0.5^\circ\text{R}$ .



TABLE 13  
(Continued)

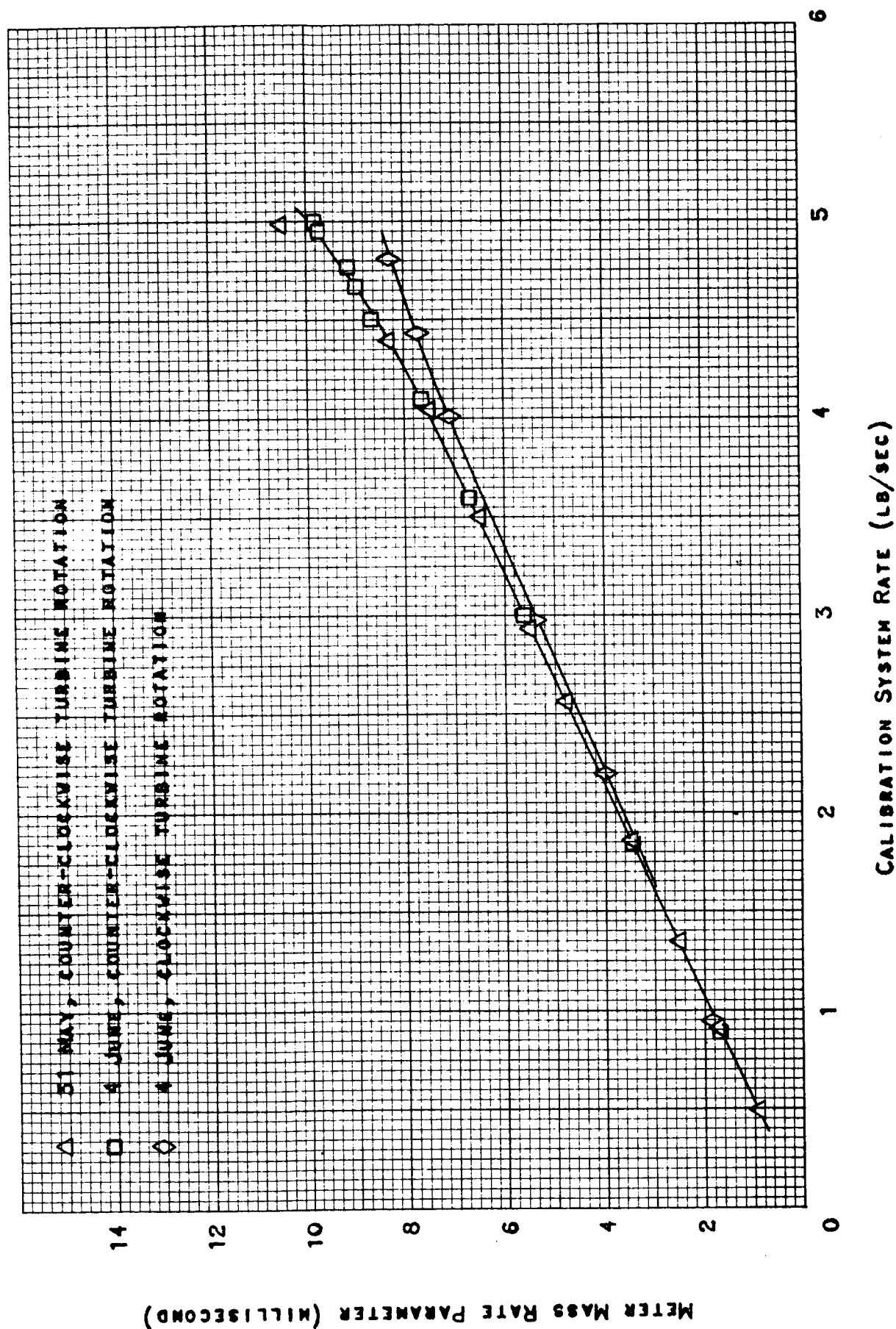
Date	Point No	System Rate (lb/sec)	Mass Rate Parameter (1/cps)	Mass Constant (1/cps · pps)
4 June Counter- Clockwise	1	0.876	$1.659 \times 10^{-3}$	$1.894 \times 10^{-3}$
	2	1.845	3.453	1.872
	3	2.987	5.589	1.871
	4	3.601	6.723	1.867
	5	4.115	7.627	1.853
	6	4.511	8.655	1.919
	7	4.667	8.946	1.917
	8	4.770	9.114	1.911
	9	4.949	9.733	1.967
	10	4.995	9.750	1.952
Clockwise	1	0.920	$1.726 \times 10^{-3}$	$1.876 \times 10^{-3}$
	2	2.190	4.004	1.828
	3	2.956	5.362	1.814
	4	4.007	7.092	1.770
	5	4.425	7.715	1.744
	6	4.841	8.298	1.714

WAUGH AXIAL MOMENTUM MASS FLOWMETER

MODEL FM-48-400, SERIAL 16161

LIQUID HYDROGEN CALIBRATION

31 MAY AND 4 JUNE 62



WAUGH AXIAL MOMENTUM MASS FLOWMETER

MODEL FM-48-400, SERIAL 16161

LIQUID HYDROGEN CALIBRATION

25, 31 MAY AND 4 JUNE 62

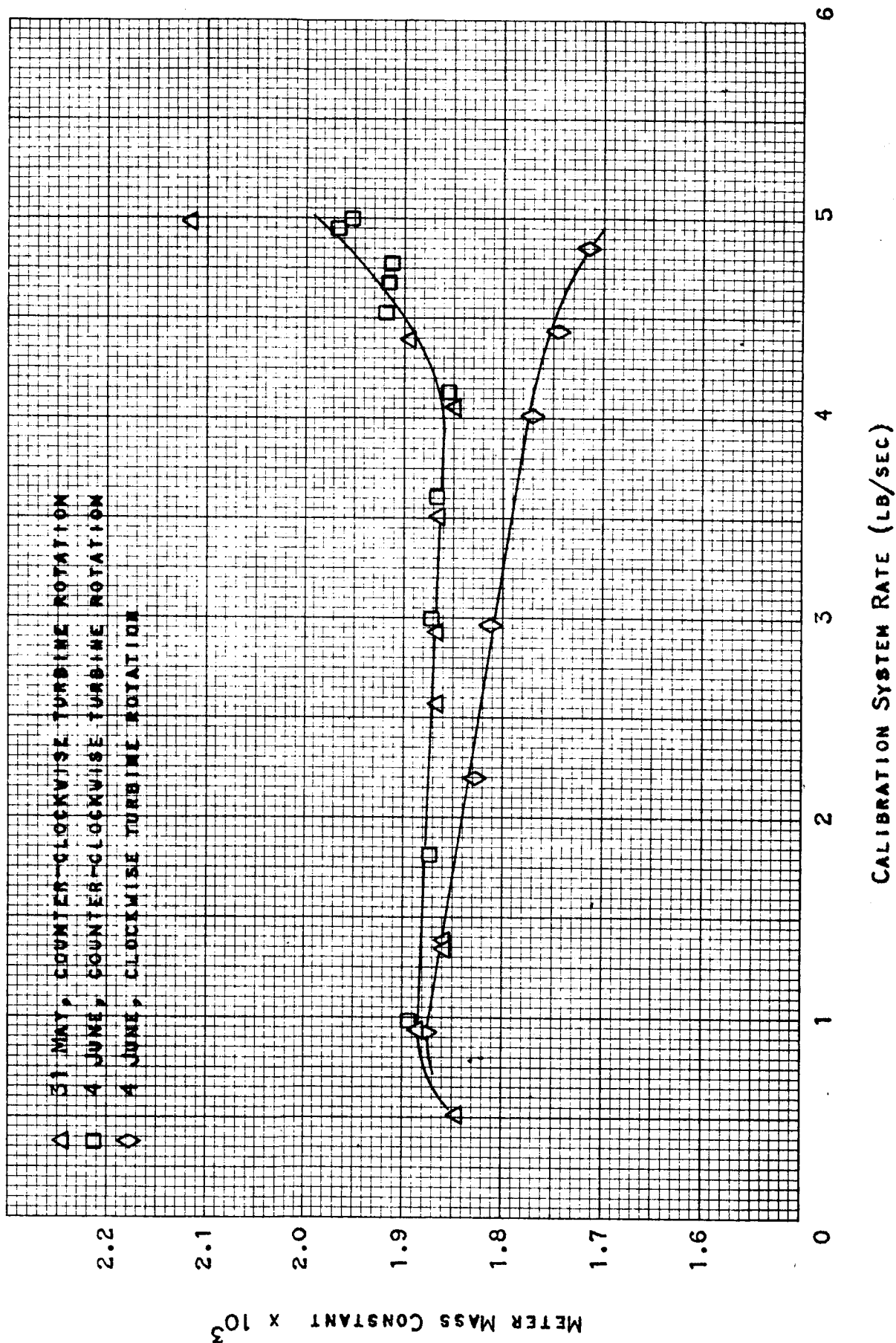


FIGURE 44

TABLE 14

WAUGH AXIAL MOMENTUM MASS FLOWMETER  
MODEL FM-48-400, SERIAL 16164  
LIQUID HYDROGEN CALIBRATION  
5 AND 6 JUNE 1962

Date	Point No.	System Rate (lb/sec)	Mass Rate Parameter (1/cps)	Mass Constant (1/cps · pps)
5 June	1	1.054	$1.742 \times 10^{-3}$	$1.653 \times 10^{-3}$
Clockwise	2	2.075	3.362	1.620
	3	3.063	4.853	1.584
	4	3.531	5.624	1.593
	5	4.092	6.389	1.561
	6	4.485	6.930	1.545
Counter Clockwise	1	0.763	$1.271 \times 10^{-3}$	$1.666 \times 10^{-3}$
	2	0.873	1.453	1.664
	3	1.323	2.182	1.649
	4	1.835	3.008	1.639
	5	2.274	3.696	1.625
	6	2.627	4.249	1.617
	7	2.919	4.712	1.614
	8	3.556	5.712	1.606
	9	3.934	6.164	1.567
	10	4.263	4.528	1.531
	11	4.476	6.942	1.551
	12	4.645	7.267	1.564
	13	4.812	7.608	1.581
	14	4.944	7.562	1.530
	15	1.140	1.875	1.645
	16	1.613	2.626	1.628
	17	2.485	3.985	1.604
	18	3.721	5.834	1.568

Note: Flowmeter inlet conditions were maintained at  $45 \pm 5$  psia. and  $38 \pm 0.5^\circ\text{R}$ .

TABLE 14  
(Continued)

Date	Point No.	System Rate (lb/sec)	Mass Rate Parameter (1/cps)	Mass Constant (1/cps · pps)
6 June	1	1.099	$1.828 \times 10^{-3}$	$1.663 \times 10^{-3}$
Clockwise	2	1.373	2.261	1.647
	3	2.085	3.398	1.630
	4	2.488	4.026	1.618
	5	3.068	4.919	1.603
	6	4.174	6.529	1.564
	7	4.565	7.101	1.556
	8	5.293	8.076	1.526
Counter- Clockwise	1	0.807	$1.335 \times 10^{-3}$	$1.654 \times 10^{-3}$
	2	1.319	2.163	1.641
	3	1.841	2.992	1.625
	4	2.258	3.654	1.618
	5	2.843	4.552	1.601
	6	3.193	5.072	1.588
	7	3.677	5.770	1.569
	8	4.173	6.410	1.536
	9	4.824	7.349	1.523
	10	4.983	7.543	1.514

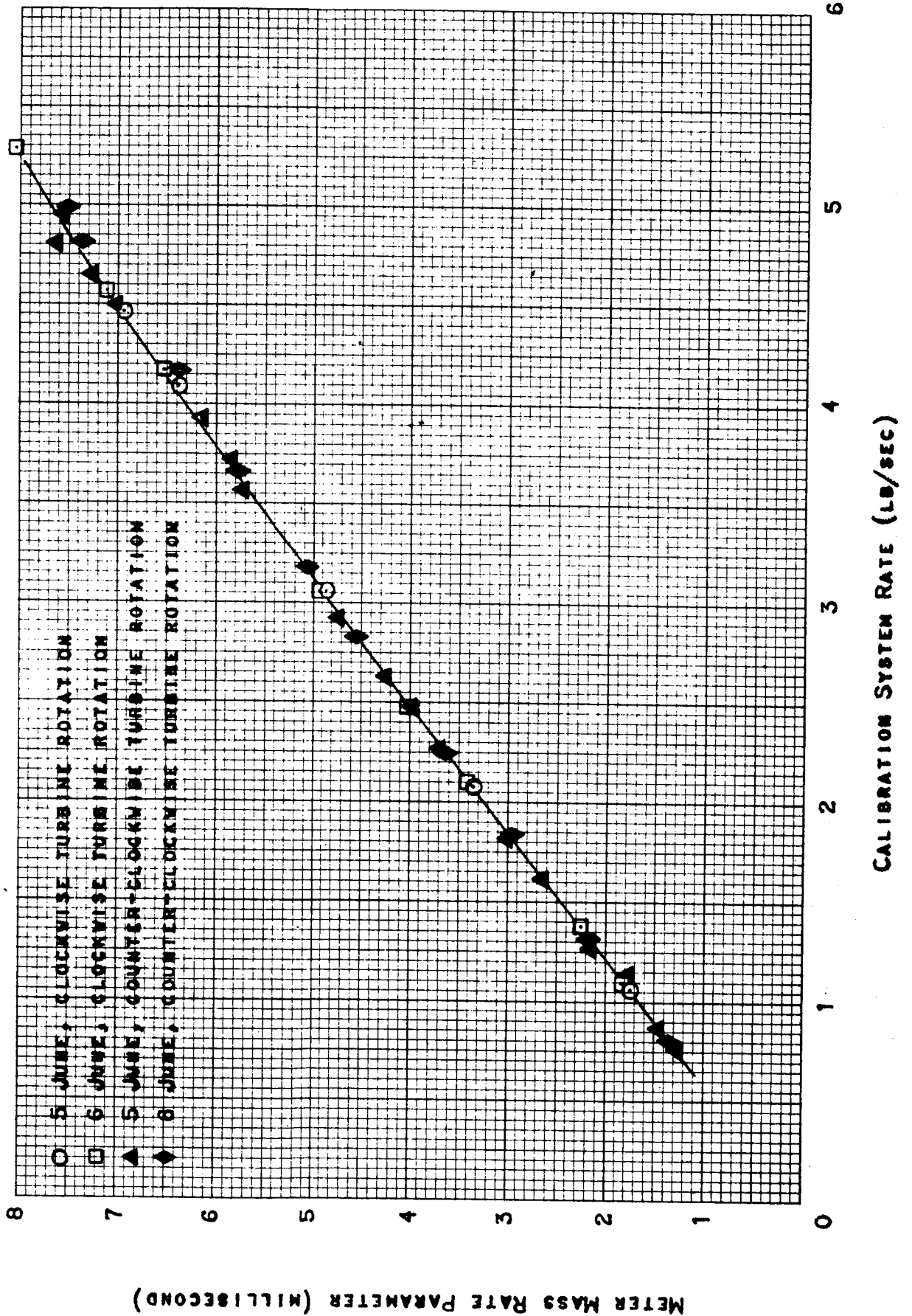
FIGURE 45

WAUGH AXIAL MOMENTUM MASS FLOWMETER

MODEL FM-48-400, SERIAL 16164

LIQUID HYDROGEN CALIBRATION

5, 6 JUNE 62



WAUGH AXIAL MOMENTUM MASS FLOWMETER

MODEL FM-48-400, SERIAL 16164

LIQUID HYDROGEN CALIBRATION

5. 6 JUNE 62

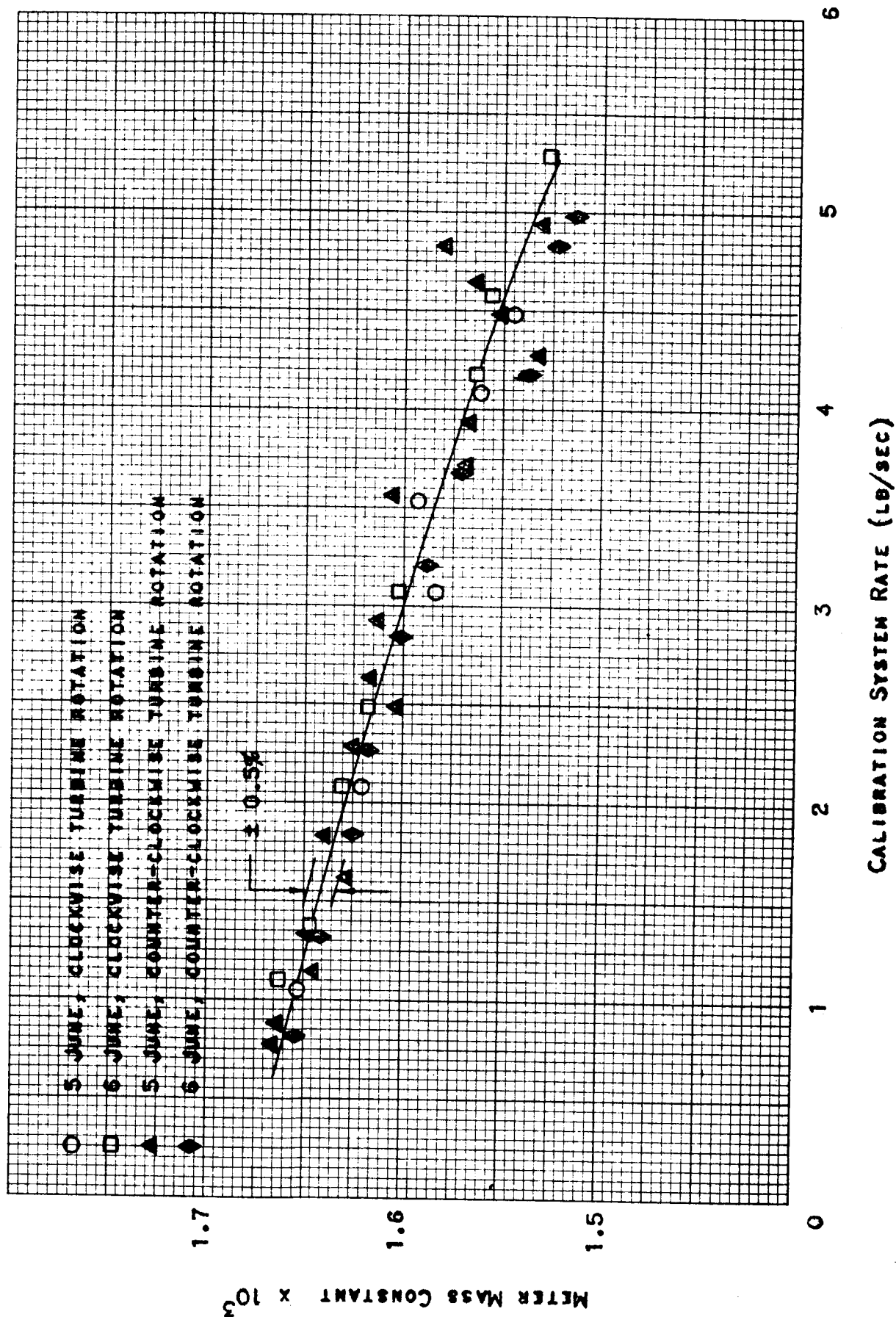


FIGURE 46

TABLE 15

WAUGH AXIAL MOMENTUM MASS FLOWMETER  
MODEL FM-48-400, SERIAL 16164  
LIQUID HYDROGEN CALIBRATION  
30 JULY AND 3 AUGUST 1962

Date	Point No.	System Rate (lb/sec)	Mass Rate Parameter (1/cps)	Mass Constant (1/cps · pps)
30 July	1	0.770	$1.283 \times 10^{-3}$	$1.666 \times 10^{-3}$
Clockwise	2	1.207	2.010	1.665
	3	1.796	2.951	1.643
	4	2.308	3.786	1.640
	5	2.651	4.368	1.648
	6	3.191	5.236	1.641
	7	3.714	6.069	1.634
	8	4.440	7.263	1.636
	9	5.358	8.792	1.641
	10	5.881	9.613	1.635
	11	6.763	10.945	1.618
	12	7.528	12.181	1.618
	13	5.932	9.650	1.627
	14	4.620	7.518	1.627
	15	3.262	5.322	1.632
	16	1.837	3.016	1.642
	17	0.822	1.369	1.665
	18	5.340	8.682	1.626
	19	5.289	8.634	1.632

Note: Flowmeter inlet conditions were maintained at  $45 \pm 5$  psia and  $38 \pm 0.5^\circ\text{R}$ .

Points 1 through 12 were performed with the upstream flowmeter (S/N 16162) rotating clockwise with points 13 through 19 performed with the upstream flowmeter (S/N 16162) rotating counter-clockwise.



TABLE 15  
(Continued)

Date	Point No.	System Rate (lb/sec)	Mass Rate Parameter (1/cps)	Mass Constant (1/cps·pps)
3 August Clockwise	1	5.174	$8.457 \times 10^{-3}$	$1.635 \times 10^{-3}$
	2	5.154	8.426	1.635
	3	4.182	6.844	1.637
	5	3.123	5.101	1.633
	6	3.084	5.002	1.641
	7	2.146	3.534	1.647
	8	0.889	1.480	1.665
	9	5.156	8.422	1.633

TABLE 16

WAUGH AXIAL MOMENTUM MASS FLOWMETER  
MODEL FM-48-400, SERIAL 16162  
LIQUID HYDROGEN CALIBRATION  
30 JULY AND 3 AUGUST 1962

Date	Point No.	System Rate (lb/sec)	Mass Rate Parameter (1/cps)	Mass Constant (1/cps · pps)
30 July	13	5.932	$8.311 \times 10^{-3}$	$1.401 \times 10^{-3}$
Counter- Clockwise	14	4.620	7.148	1.547
	15	3.262	5.540	1.698
	16	1.837	3.389	1.845
	17	0.822	1.624	1.976
	18	5.340	7.832	1.467
	19	5.289	7.780	1.471
3 August	1	5.174	$7.987 \times 10^{-3}$	$1.544 \times 10^{-3}$
Counter- Clockwise	2	5.154	7.901	1.533
	3	4.182	6.715	1.606
	5	3.123	5.343	1.711
	6	3.084	5.310	1.722
	7	2.146	3.912	1.823
	8	0.889	1.750	1.969
	9	5.156	7.626	1.479

Note: Flowmeter inlet conditions were maintained at  $45 \pm 5$  psi  
and  $38 \pm 0.5^\circ\text{R}$ .

WAUGH AXIAL MOMENTUM MASS FLOWMETER  
MODEL FM-48-400, SERIAL 16162 AND 16164

LIQUID HYDROGEN CALIBRATION

30 JULY AND 3 AUGUST 62

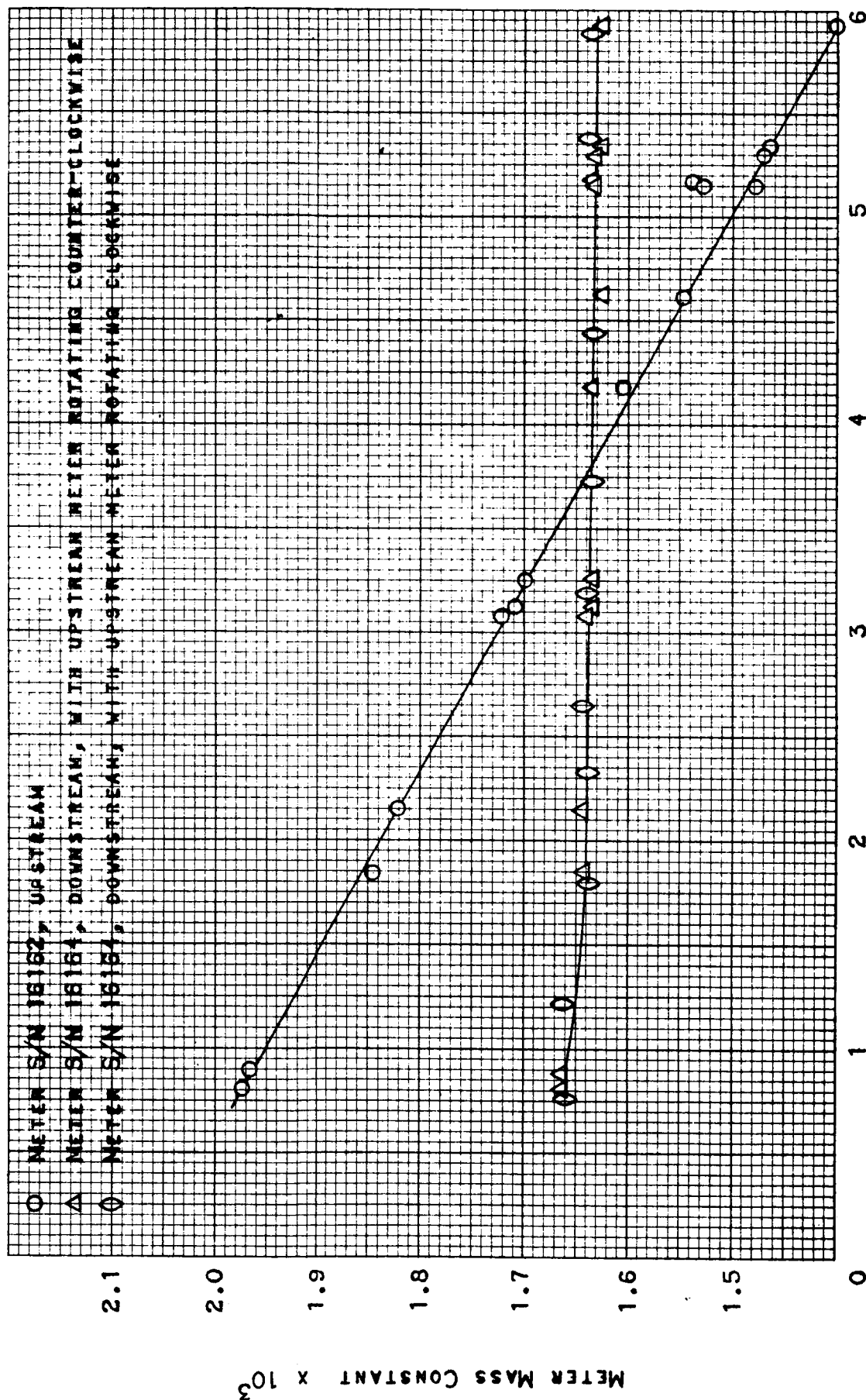


FIGURE 47

TABLE 17

WAUGH AXIAL MOMENTUM MASS FLOWMETER  
MODEL FM-48-400, SERIAL 16163  
LIQUID HYDROGEN CALIBRATION  
6 AND 7 FEBRUARY 1963  
 (Downstream)

Date	Point No.	System Rate (lb/sec)	Mass Rate Parameter (1/cps)	Mass Constant (1/cps · pps)
6 February	1	4.146	$13.410 \times 10^{-3}$	$3.234 \times 10^{-3}$
Counter- Clockwise	2	4.161	13.500	3.244
	3	6.255	20.180	3.226
	4	6.269	20.430	3.259
	5	7.715	24.390	3.161
	6	7.724	24.500	3.172
	7	8.734	29.870	3.420
	9	8.734	30.270	3.466
	10	9.545	35.570	3.729
	11	9.542	33.640	3.525
	12	10.120	32.770	3.238
	13	10.127	52.190	5.154
	14	11.256	44.480	3.952
	15	11.375	47.480	4.174
	16	2.508	8.145	3.248
	17	2.481	8.091	3.261
	18	0.821	2.718	3.311
	19	0.819	2.720	3.321

Note: Flowmeter inlet conditions were maintained at  $45 \pm 5$  psia  
and  $38 \pm 0.5^\circ\text{R}$ .

TABLE 17  
(Continued)

Date	Point No.	System Rate (lb/sec)	Mass Rate Parameter (1/cps)	Mass Constant (1/cps · pps)
7 February	2	5.420	$17.070 \times 10^{-3}$	$3.149 \times 10^{-3}$
Counter- Clockwise	3	3.355	10.741	3.201
	4	3.330	10.675	3.206
	5	5.399	17.427	3.228
	6	1.343	4.384	3.264
	7	1.340	4.372	3.263
	9	7.177	22.893	3.190
	10	7.189	23.391	3.254
	11	8.377	26.406	3.152
	12	8.482	26.759	3.155
	13	1.089	3.574	3.282
	14	1.084	3.563	3.287
	15	1.924	6.247	3.247

TABLE 18

WAUGH AXIAL MOMENTUM MASS FLOWMETER  
MODEL FM-48-400, SERIAL 16164  
LIQUID HYDROGEN CALIBRATION  
6 AND 7 FEBRUARY 1963  
 (Upstream)

Date	Point No.	System Rate (lb/sec)	Mass Rate Parameter (1/cps)	Mass Constant (1/cps · pps)
6 February	1	4.146	$6.122 \times 10^{-3}$	$1.477 \times 10^{-3}$
Counter- Clockwise	2	4.161	6.168	1.482
	3	6.255	8.977	1.435
	4	6.269	9.033	1.441
	5	7.715	10.816	1.402
	6	7.724	10.871	1.407
	7	8.734	12.943	1.482
	9	8.734	12.861	1.473
	10	9.545	13.522	1.417
	11	9.542	13.210	1.385
	12	10.120	13.646	1.348
	13	10.127	14.056	1.388
	14	11.256	14.916	1.325
	15	11.375	15.503	1.363
	16	2.508	3.881	1.547
	17	2.481	3.833	1.545
	18	0.821	1.275	1.553
	19	0.819	1.278	1.560

Note: Flowmeter inlet conditions were maintained at  $45 \pm 5$  psia  
and  $38 \pm 0.5^\circ\text{R}$ .

TABLE 18  
(Continued)

Date	Point No.	System Rate (lb/sec)	Mass Rate Parameter (1/cps)	Mass Constant (1/cps · pps)
7 February	2	5.420	$8.028 \times 10^{-3}$	$1.481 \times 10^{-3}$
Counter- Clockwise	3	3.355	5.106	1.522
	4	3.330	5.067	1.522
	5	5.399	8.005	1.482
	6	1.343	2.052	1.528
	7	1.340	2.077	1.550
	9	7.177	10.419	1.452
	10	7.189	10.262	1.427
	11	8.377	11.323	1.352
	12	8.482	11.290	1.331
	13	1.089	1.716	1.575
	14	1.084	1.717	1.584
	15	1.924	2.961	1.539

TABLE 19

WAUGH AXIAL MOMENTUM MASS FLOWMETER  
MODEL FM-48-400, SERIAL 16164  
LIQUID HYDROGEN CALIBRATION  
20 FEBRUARY 1963  
 (Downstream)

Date	Point No.	System Rate (lb/sec)	Mass Rate Parameter (1/cps)	Mass Constant (1/cps · pps)
20 February Counter- Clockwise	2	4.209	$6.538 \times 10^{-3}$	$1.553 \times 10^{-3}$
	3	4.194	6.555	1.563
	4	6.388	9.746	1.526
	5	6.450	9.803	1.520
	6	7.779	11.703	1.504
	7	2.401	3.825	1.593
	8	2.421	3.848	1.589
	9	0.823	1.329	1.615
	10	0.836	1.349	1.614
	11	1.331	2.145	1.612
	12	1.334	2.144	1.607
	13	3.368	5.292	1.571
	14	3.355	5.277	1.573
	15	5.430	8.383	1.544

Note: Flowmeter inlet conditions were maintained at  $45 \pm 5$  psia and  $38 \pm 0.5^\circ\text{R}$ .



TABLE 20

WAUGH AXIAL MOMENTUM MASS FLOWMETER  
MODEL FM-48-400, SERIAL 16162  
LIQUID HYDROGEN CALIBRATION  
20 FEBRUARY 1963  
(Upstream)

Date	Point No.	System Rate (lb/sec)	Mass Rate Parameter (l/cps)	Mass Constant (l/cps · pps)
20 February	2	4.209	$12.874 \times 10^{-3}$	$3.059 \times 10^{-3}$
Counter- Clockwise	3	4.194	13.127	3.142
	4	6.388	16.343	2.558
	5	6.450	16.479	2.555
	6	7.779	16.679	2.144
	7	2.401	8.362	3.483
	8	2.421	8.213	3.392
	9	0.823	2.612	3.174
	10	0.836	2.662	3.184
	11	1.331	4.246	3.190
	12	1.334	4.248	3.184
	13	3.368	11.497	3.414
	14	3.355	11.558	3.445
	15	5.430	16.182	2.980

Note: Flowmeter inlet conditions were maintained at  $45 \pm 5$  psia  
and  $38 \pm 0.5^{\circ}\text{R}$ .

FIGURE 48

WAUGH AXIAL MOMENTUM MASS FLOWMETER

MODEL FM-48-400, SERIAL 16164

LIQUID HYDROGEN CALIBRATION

6, 7, 20 FEBRUARY 63

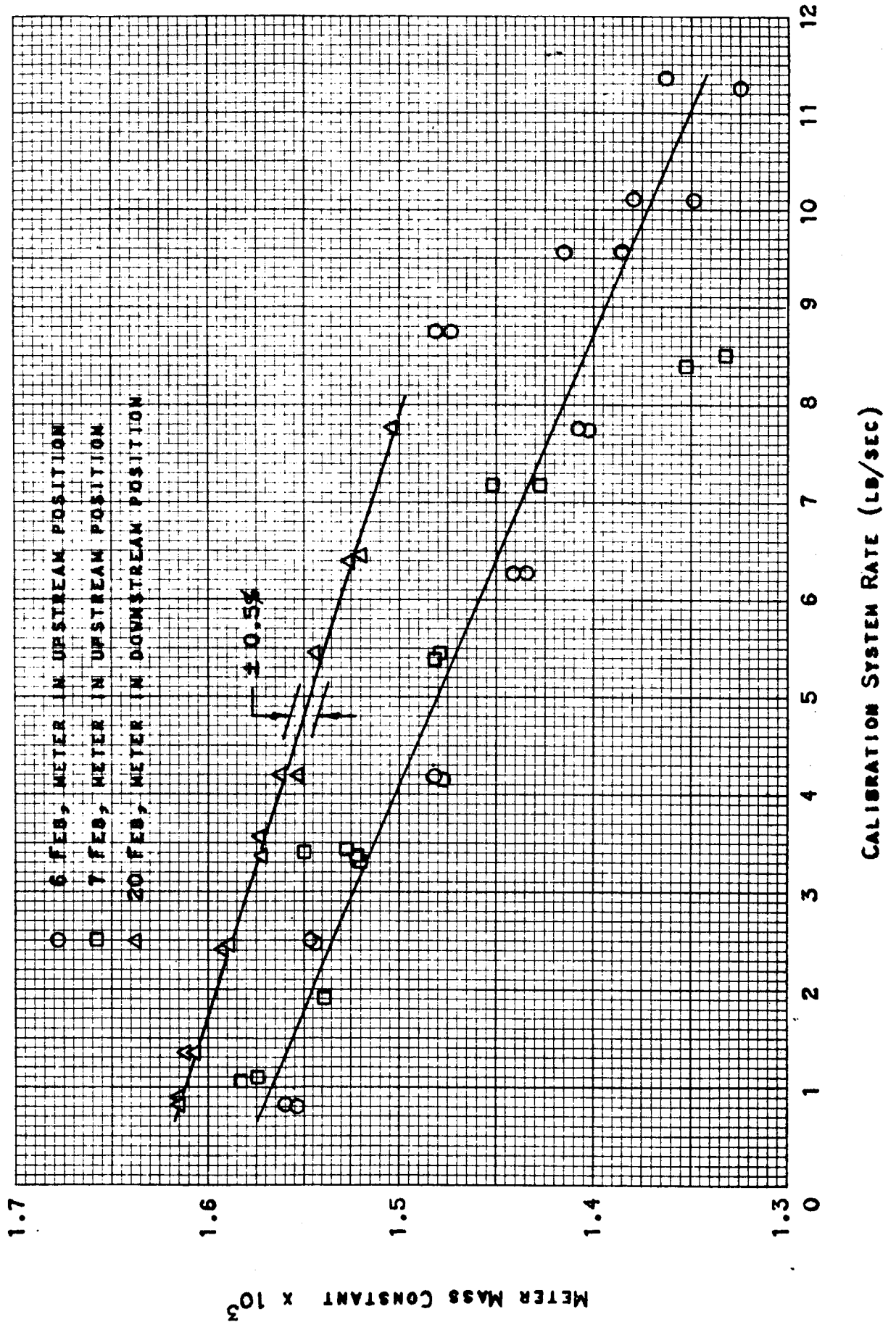


TABLE 21

WAUGH AXIAL MOMENTUM MASS FLOWMETER  
MODEL FM-48-400, SERIAL 16162 and 16164  
LIQUID HYDROGEN-GASEOUS HELIUM DUAL PHASE CALIBRATION  
1, 3 AUGUST 1962

Date & Point No.	System Rate (lb/sec)	Volumetric Gas/Liquid Ratio (percent)	S/N 16164 Mass Constant (1/cps pps)	S/N 16162 Mass Constant (1/cps pps)
1 August				
6	4.698	7.0	1.609	1.513
7	4.807	6.5	1.609	1.500
8	4.781	6.7	1.613	1.501
9	4.847	6.3	1.623	1.500
10	4.986	6.7	1.622	1.490
11	4.842	6.7	1.622	1.514
12	4.812	6.7	1.624	1.511
13	4.485	10.4	1.619	1.549
14	4.676	9.7	1.620	1.526
15	4.829	9.2	1.621	1.511
16	4.987	9.3	1.626	1.494
17	5.096	10.2	1.627	1.473
18	4.892	9.5	1.633	1.505

Notes: S/N 16162, upstream with clockwise turbine rotation  
S/N 16164, downstream with counter-clockwise turbine rotation  
Flowmeter inlet conditions were maintained at  $45 \pm 5$  psia and  
 $38 \pm 0.5^{\circ}\text{R}$ .

TABLE 21  
(Continued)

Date & Point No.	System Rate (lb/sec)	Volumetric Gas/Liquid Ratio (percent)	S/N 16164 Mass Constant (1/cps pps)	S/N 16162 Mass Constant (1/cps · pps)
10	4.647	8.8	1.602	1.521
11	4.957	4.9	1.622	1.498
12	5.170	4.2	1.629	1.465
13	4.651	12.0	1.605	1.529
14	4.703	12.0	1.604	1.506
15	4.759	12.0	1.596	1.480
16	4.744	11.0	1.559	1.449
17	4.747	9.9	1.462	1.429
18	4.965	7.0	1.503	1.382

Note: S/N 16162, upstream with clockwise turbine rotation.  
S/N 16164, downstream with counter-clockwise turbine rotation.

WAUGH AXIAL MOMENTUM MASS FLOWMETER  
MODEL FM-48-400, SERIAL 16162 AND 16164  
LIQUID HYDROGEN-GASEOUS HELIUM DUAL PHASE CALIBRATION

1. 3 AUGUST 62

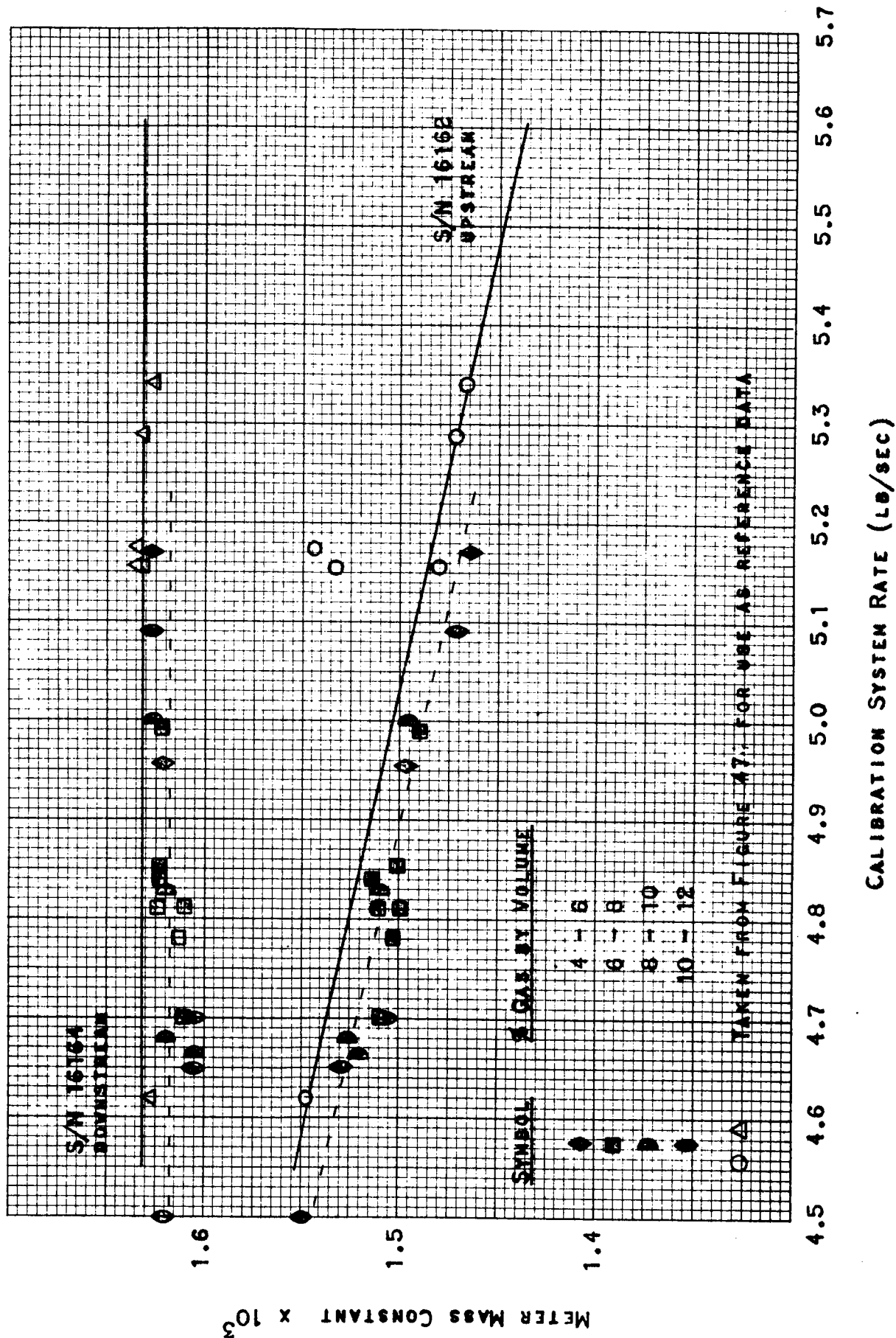
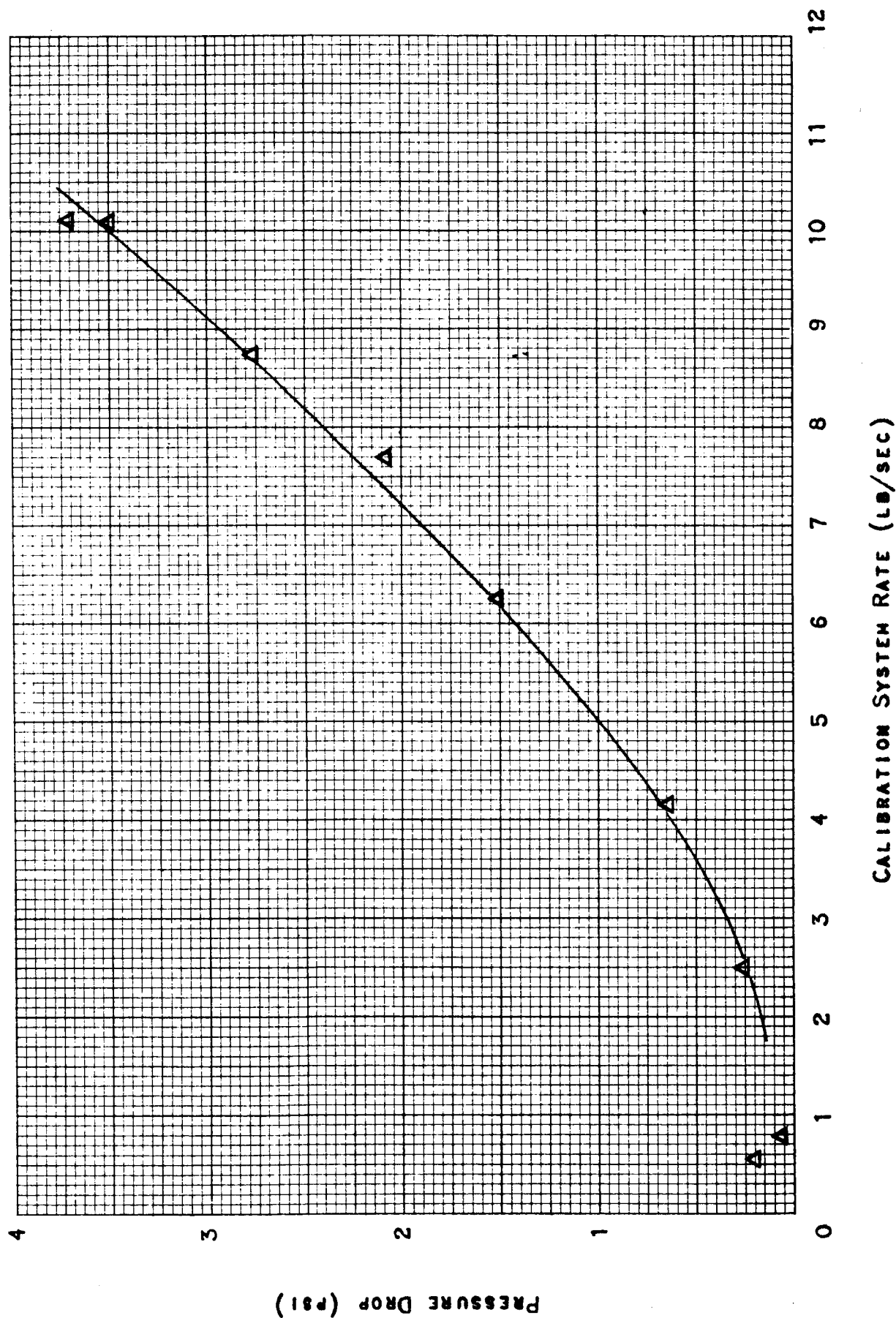


FIGURE 50

WAUGH AXIAL MOMENTUM MASS FLOWMETER

MODEL FM-48-400

LIQUID HYDROGEN PRESSURE DROP CHARACTERISTICS



## EVALUATION OF THE GENERAL ELECTRIC CORPORATION ANGULAR MOMENTUM MASS FLOWMETER

### Description

The General Electric mass flowmeter, Model TJ-64, shown in Figure 51 operates on an angular momentum principle. The flowmeter consists of a constant speed, motor driven, impeller which imparts an angular velocity to the fluid passing through the flowmeter. Immediately downstream, a turbine which is free to rotate against a constant torque restraining spring absorbs the angular momentum imparted to the fluid by the impeller. The spring-restrained turbine deflects through an angle proportional to the torque exerted by the fluid, which is directly proportional to the product of the mass-flow rate and the upstream impeller speed.

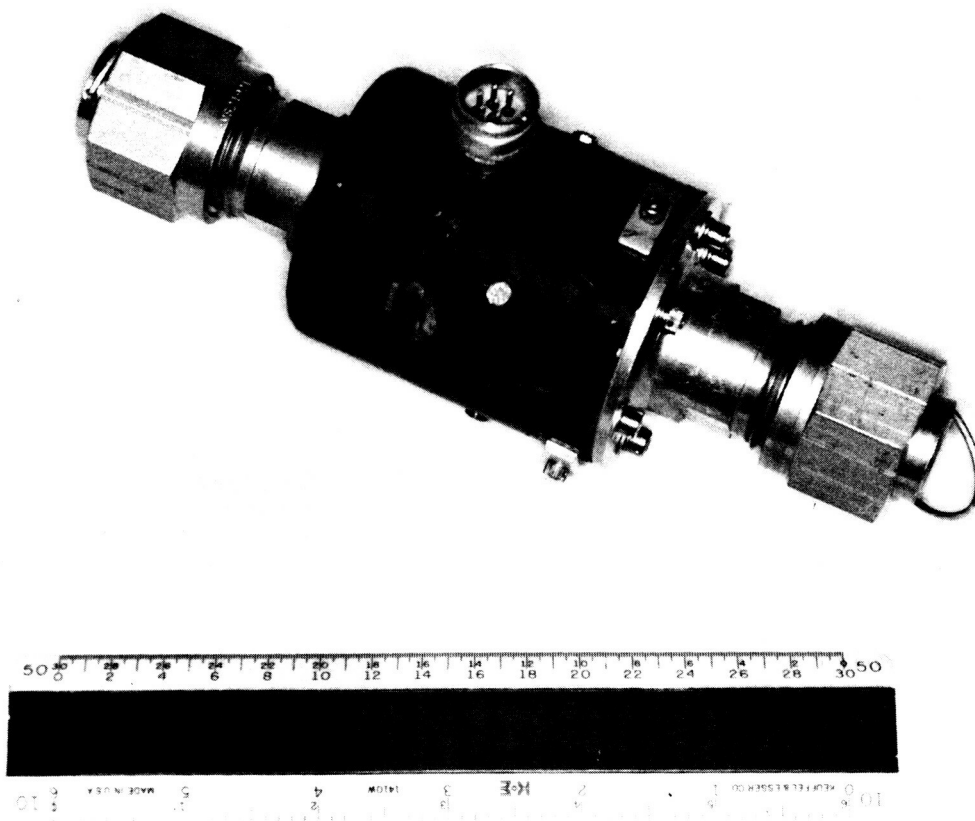
The displacement of the turbine, which is proportional to the mass-flow rate, is transmitted through a selsyn system and displayed on a dial indicator. During the performance of the calibration work with this flowmeter, a 6-inch master indicator was utilized to observe the flowmeter output, rather than the small flight hardware indicators normally used with this equipment.

Advantages of the General Electric mass flowmeter may be briefly summarized as follows:

1. The primary output is a rate signal, and ideally suited for systems where rate indicators are of primary importance.
2. Since there are no turbines which rotate at velocities proportional to the fluid velocity, there is no potential overspeeding problem during two-phase operation.

Some characteristics which might be considered undesirable in certain applications would be:

1. The analog output signal is less convenient to use when totalized flow is required.
2. An external power source is required to drive the upstream impeller.



GENERAL ELECTRIC MASS FLOWMETER  
MODEL TJ-64 SERIAL AES 1005

FIGURE 51



It should be noted that the Model TJ-64 flowmeter was a slightly modified commercial jet-fuel flowmeter, primarily designed to operate at ambient temperatures and fluid densities commensurate with kerosene base fuels. The following modifications were made prior to the cryogenic tests:

1. The bearing materials were changed to accommodate cryogenic service.
2. The body housing rubber "O" ring seal was replaced with a teflon coated sealing ring.
3. The impeller pick-off magnets were mechanically secured in lieu of the adhesive bonding techniques normally used.

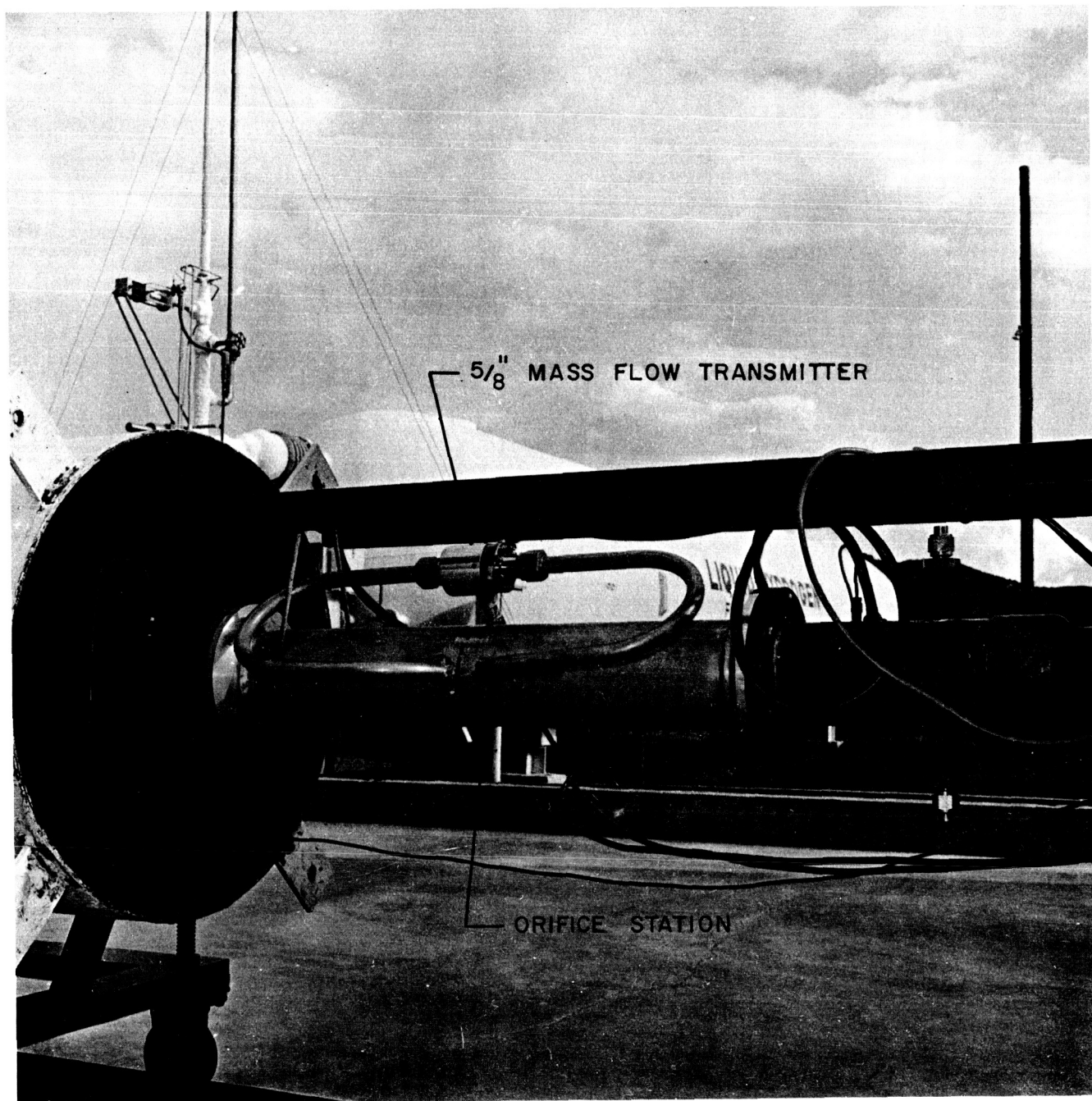
A second series of tests was performed during this program with a flowmeter system which utilized a 5/8-inch mass flowmeter, Model Z-809,, in parallel with a restricting orifice in a nominal 4-inch diameter line. This system is shown in Figure 52.

The Model Z-809 flowmeter operates on the same principle as the Model TJ-64 unit previously described, with the exception that the output signal is a 400 cps single phase voltage which is proportional to the mass flow rate.

Several additional advantages associated with the by-pass flowmetering technique are:

1. The size of the sensing element and subsequent costs is greatly reduced.
2. Lower system pressure drop.
3. Bi-directional flow measuring system could be assembled without increasing the pressure drop over a uni-directional system.

As previously stated, it should be pointed out that the system described herein is a prototype unit and it would be expected that performance would be improved with additional development work.



GENERAL ELECTRIC MASS FLOWMETER MODEL Z-809

FIGURE 52

## Discussion of Test Data Obtained with the Model TJ-64 Flowmeter

During the performance of the calibration of the 1/2-inch Model TJ-64 mass flowmeter, the flow rate output indication was observed visually on a 6-inch master selsyn indicator. The flowmeter installed in the calibration system is shown in Figure 53.

Approximately 20 calibration points were obtained during the preliminary tests of October 5 through 8, 1962 and resulted in data which was repeatable at specific flow rates, but extremely erratic over the total flow range. This preliminary data is presented in Table 22 and Figure 54. Following this initial calibration the flowmeter was removed from the system and disassembled by the manufacturer's representative. It was noted at this time that the core and coil assemblies were loose and were subsequently resecured to the flowmeter housing prior to performing subsequent tests. In addition, the length of the 1/2-inch diameter tubing upstream and downstream of the flowmeter was increased to provide a more uniform inlet flow condition. The calibrations of October 5 through 8 were performed with 1-inch to 1/2-inch tube transition sections immediately upstream and downstream of the flowmeter.

A second series of tests was performed November 29 through December 4 and resulted in the acquisition of approximately 30 data points. The data obtained during these runs was greatly improved, as evidenced by the data presented in Table 23 and Figures 55 and 56. The performance of the flowmeter below 12 ppm was attributed to two-phase flow conditions resulting from inadequate thermal insulation upstream of the flowmeter and the change in the flowmeter output above 28.5 ppm was attributed to extremely high line velocities. Because of the small size of the flowmeter, and correspondingly low flow rates, the existing calibration system was not ideally suited to evaluation of this flowmeter.

In order to establish the potential performance level for the flowmeter a linear RMS curve was calculated for the data points between 11.5 and 28.5 lb/min. This evaluation indicated a data spread in the limited flow range of less than  $\pm 0.5\%$ . The pressure drop characteristic obtained during the performance of these tests is presented in Figure 57.



FIGURE 53

GENERAL ELECTRIC MASS FLOWMETER MODEL TJ-64

## Discussion of Test Data Obtained with Model Z-809 Bypass Flowmeter

The Model Z-809 flowmeter submitted for evaluation during the second phase of the program utilizes the principle of a flow dividing orifice, allowing the use of a flow rate sensing transmitter which is smaller than the nominal size of the main stream piping. This particular flowmeter consists of a 4-inch diameter tube incorporating an orifice to divide the flow through a nominal 5/8-inch mass flowmeter. The mass flowmeter generates a 400 cps single phase voltage which is proportional to the mass flow rate. In addition, an integrator was supplied with the system to supply a totalized output. During the calibrations, the mass rate signal was observed on a vacuum tube voltmeter and the integrator output read directly from the General Electric Company's equipment.

Preliminary calibration tests were performed April 2, 1963. During these calibrations considerable data scatter was observed and testing was discontinued. It was determined that the mechanical portion of the integrator system was binding, and the manufacturer's representative repaired the integrator prior to performing additional tests.

On April 3, 1963, 26 data points were obtained from the 4-inch bypass system over a flow range of 1 through 12 lb/sec. The flow proportional voltage which was measured during each calibration run was plotted versus the average flow rate determined from the calibration stand. Subsequently, a least square linear evaluation of the data from 0 to 10 pps was performed, and indicated a point deviation of approximately  $\pm 1\%$ . It should be noted that the readability of the voltmeter utilized to obtain this data was  $\pm 0.01$  volts in the 0 to 3 volt range, and  $\pm 0.02$  volts in the 0 to 10 volt range.

To obtain an indication of the integrator performance, the totalized output of the integrator was compared to the total transferred weight from the calibration stand, and a least square evaluation made of this data from 0 to 10 pps, indicating a maximum point deviation of approximately  $\pm 3.0\%$ . It is felt that the integrator was not operating properly during these tests as evidenced by the initial malfunction of the unit. The data obtained during these calibrations is presented in Table 24 and Figures 58 and 59. The pressure drop data obtained is presented in Figure 60.

On May 10, 1963 flowmeter Model Z-809 was subjected to single and two-phase calibration tests to evaluate the flowmeter's performance during two-phase flow conditions. Initial tests were conducted with single-phase liquid hydrogen flow to establish the flowmeter's single-phase performance. Five two-phase flow tests were conducted with helium gas to liquid hydrogen volumetric ratios ranging from 7% to approximately 14%. The flowmeter exhibited only minor sensitivity to the two-phase flow conditions for gas to liquid ratios up to 14%. The two-phase data, as presented in Table 25 and Figure 61, indicates a data scatter of approximately  $\pm 1\%$ .

TABLE 22

GENERAL ELECTRIC MASS FLOWMETER  
MODEL TJ-64, SERIAL AES 1005  
LIQUID HYDROGEN CALIBRATION  
5, 6, 8 OCTOBER 1962

Date	Point No..	System Rate (lb/min)	Mass Rate Parameter (degrees)	Average Mass Constant (degrees/ppm)
5 October 1962	7	28.25	233/234	8.27
	8	34.61	252/252	7.28
	9	39.46	309/309	7.83
	10	35.28	290/289	8.21
	11	30.18	240/240	7.95
	12	27.07	212/209	7.78
	13	25.22	190/189	7.52
	14	18.26	131/128	7.09
6 October 1962	1	36.68	299/299	8.15
	2	26.04	192/193	7.39
	3	13.84	100/95	7.05
	4	32.31	248/246	7.65
	5	21.40	144/142	6.69
	6	36.08	260/256	7.16
	7	27.61	224/223	8.10
	9	17.61	126/121	7.02
8 October 1962	1	37.40	301/300	8.04
	2	33.82	249/248	7.35
	3	26.59	195/192	7.28
	4	21.60	144/140	6.58
	5	12.98	97/95	6.63

Note: Flowmeter inlet conditions were maintained at  $55 \pm 5$  psia and  $38.5 \pm 0.5^{\circ}\text{R}$ .

FIGURE 54

GENERAL ELECTRIC MASS FLOWMETER

MODEL TJ-64, SERIAL AES1005

LIQUID HYDROGEN CALIBRATION

5, 6, 8 OCTOBER 62

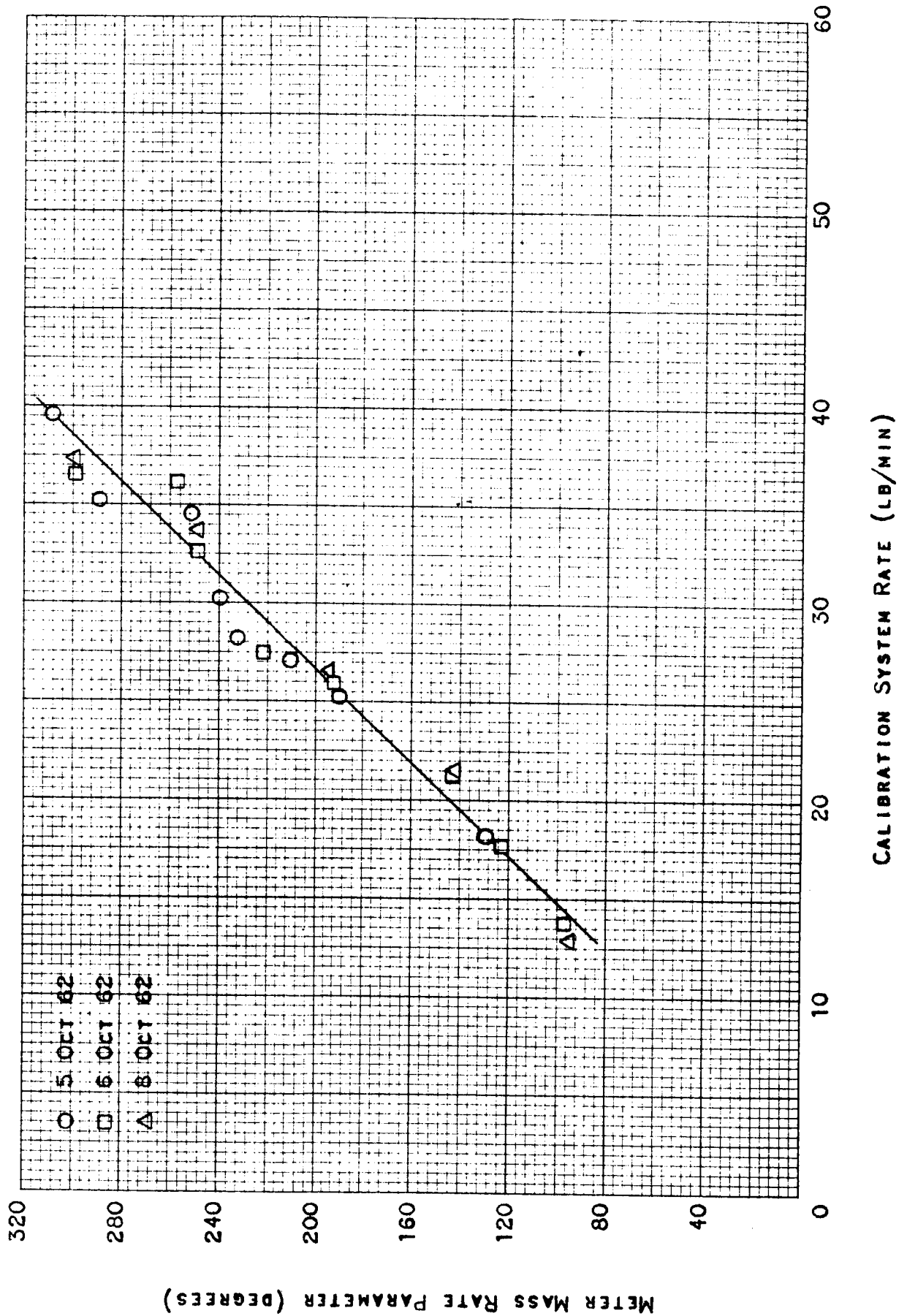




TABLE 23

GENERAL ELECTRIC MASS FLOWMETER  
MODEL TJ-64, SERIAL AES 1005  
LIQUID HYDROGEN CALIBRATION  
29, 30 NOVEMBER AND 4 DECEMBER 1962

Date	Point No.	System Rate (lb/min)	Mass Rate Parameter (degrees)	Average Mass Constant (degrees/ppm)
29 November 1962	2	35.20	255/255	7.245
	3	35.46	256/257	7.234
	4	35.71	259/259	7.253
	5	29.58	235/235	7.945
	6	29.03	233/233	8.027
	7	28.82	233/233	8.084
	8	28.69	231/232	8.069
	9	16.82	120/117	7.046
	11	16.67	119/115	7.021
	12	21.74	165/164	7.567
	13	21.70	165/164	7.580
	16	24.90	193/192	7.732
	17	25.00	194/193	7.739
	18	13.42	92/89	6.745
30 November 1962	1	34.63	252/252	7.278
	3	34.88	254/253	7.268
	4	11.77	80/76	6.628
	5	12.09	82/78	6.616
	6	12.28	84/79	6.637

Note: Flowmeter inlet conditions were maintained at  $55 \pm 5$  psia and  $38.5 \pm 0.5^\circ\text{R}$ .

TABLE 23  
(Continued)

Date	Point No.	System Rate (lb/min)	Mass Rate Parameter (degrees)	Average Mass Constant (degrees/ppm)
4 December 1962	1	31.58	242/242	7.664
	2	31.43	241/240	7.652
	3	28.98	234/232	8.041
	4	28.68	233/231	8.088
	8	23.09	175/174	7.559
	9	22.86	174/173	7.590
	10	3.85	27/25	6.762
	11	7.41	55/47	6.817

GENERAL ELECTRIC MASS FLOWMETER  
MODEL TJ-64, SERIAL AES1005  
LIQUID HYDROGEN CALIBRATION  
29, 30 NOVEMBER AND 4 DECEMBER 62

FIGURE 55

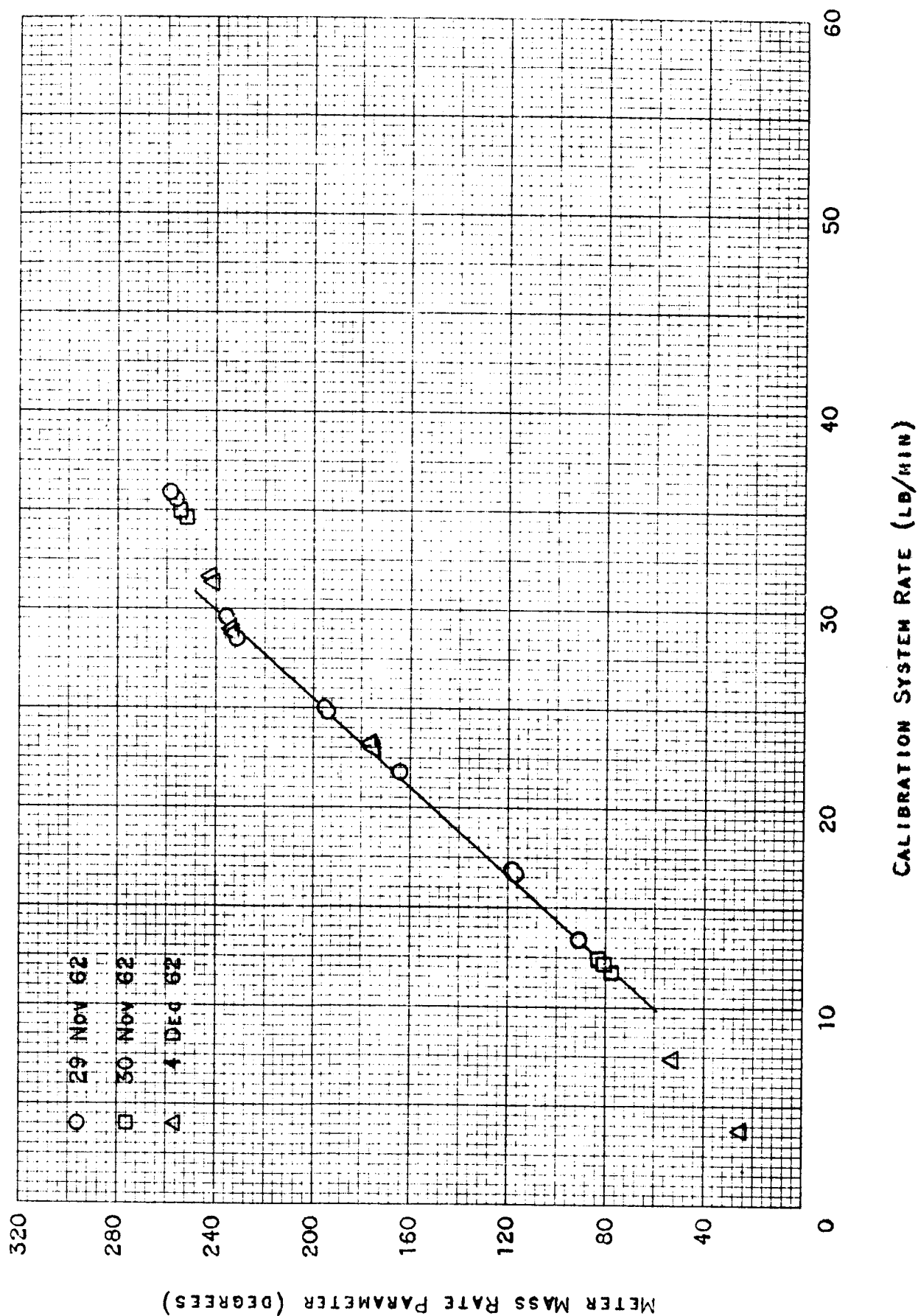


FIGURE 56

GENERAL ELECTRIC MASS FLOWMETER  
MODEL TJ-64, SERIAL AES1005  
LIQUID HYDROGEN CALIBRATION  
29, 30 NOVEMBER AND 4 DECEMBER 62

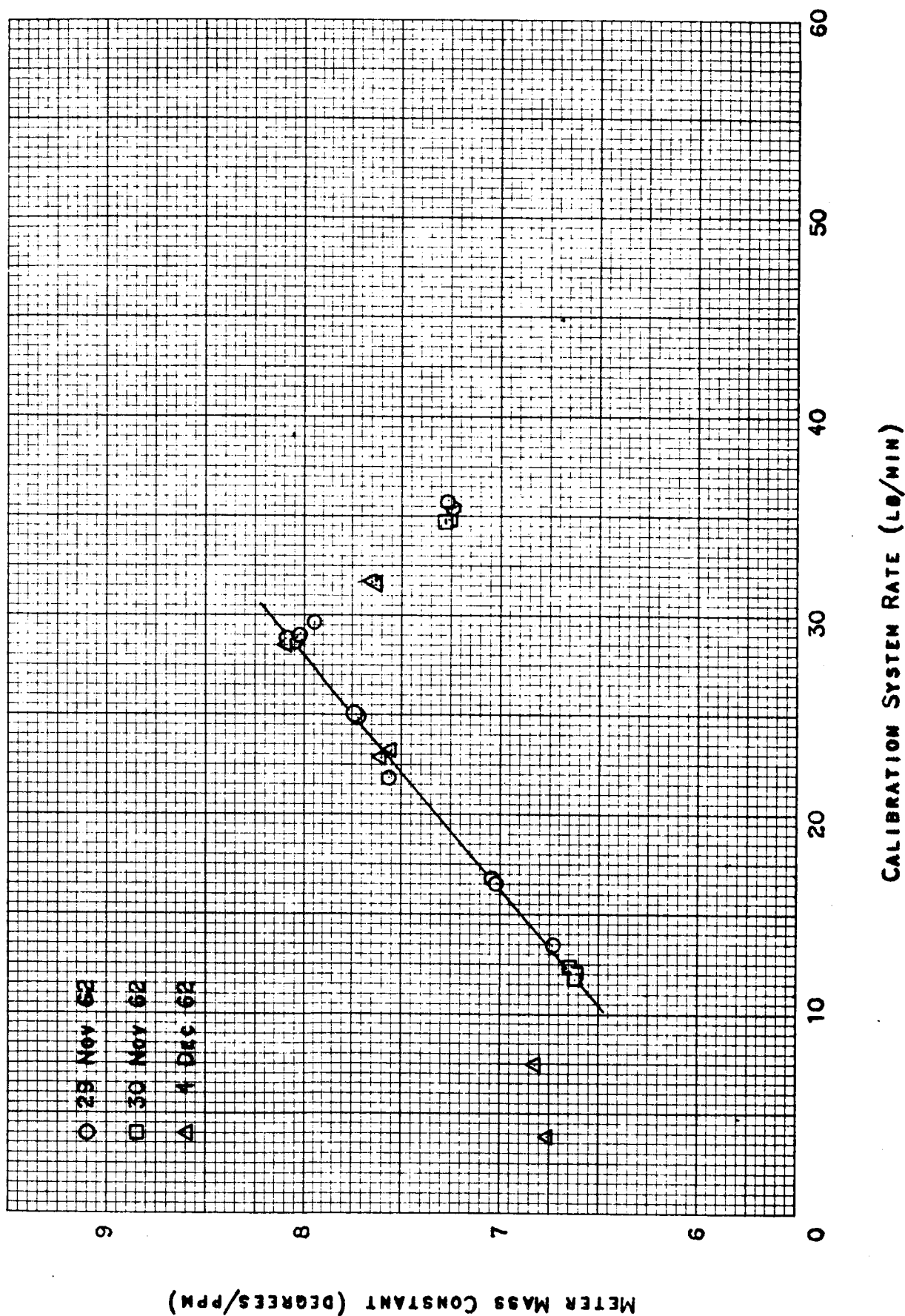


FIGURE 57

GENERAL ELECTRIC MASS FLOWMETER

MODEL TJ-64, SERIAL AES1005

LIQUID HYDROGEN PRESSURE DROP CHARACTERISTICS

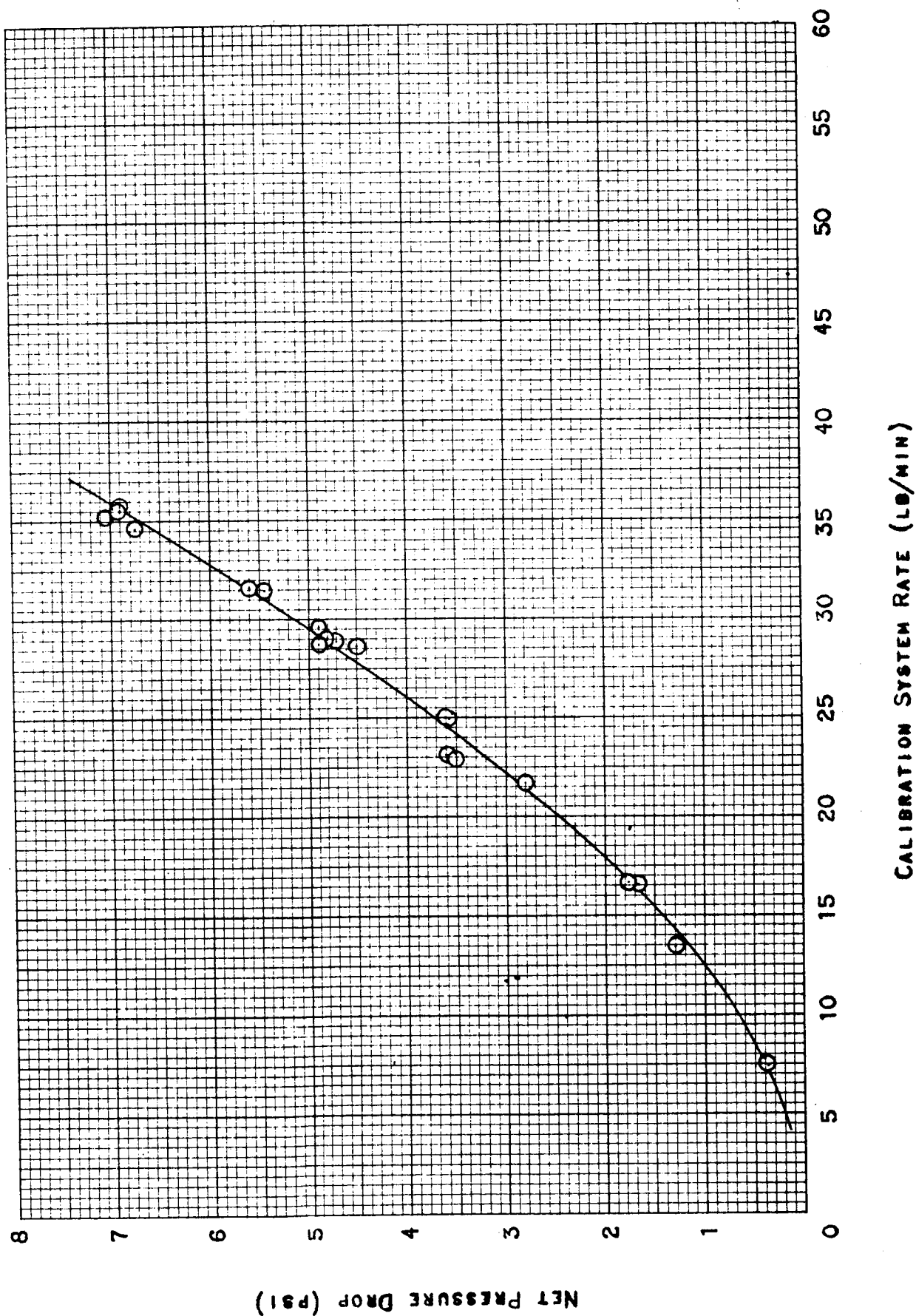


TABLE 24

GENERAL ELECTRIC BYPASS FLOWMETER  
MODEL Z-809  
LIQUID HYDROGEN CALIBRATION  
3 APRIL 1963

Point No.	System Rate (lb/sec)	Integrator Output (lb)	Integration Constant (lb/lb)	Mass Rate Parameter (volts)
1	3.958	204.6	1.023	2.50
2	3.975	208.9	1.045	2.50
3	0.954	281.7	1.408	1.04
4	0.965	285.5	1.428	1.05
5	2.185	237.9	1.189	1.65
6	2.167	235.1	1.175	1.63
7	3.042	218.2	1.091	2.04
8	3.048	219.4	1.097	2.07
9	3.967	209.4	1.047	2.50
10	4.014	206.9	1.035	2.50
12	6.059	192.6	0.963	3.50
13	6.086	193.8	0.969	3.50
14	7.327	196.0	0.980	4.20
15	7.434	192.5	0.962	4.20
16	8.706	194.0	0.970	4.85
17	8.666	189.0	0.945	4.80
18	9.658	186.3	0.931	5.30
19	9.682	184.2	0.921	5.20
20	10.575	182.2	0.911	5.60
21	10.636	175.8	0.879	5.50
22	12.121	173.0	0.865	6.40
23	12.220	175.2	0.876	6.40
25	5.236	195.0	0.975	3.10
26	1.821	254.3	1.271	1.48

Note: Flowmeter inlet conditions were maintained at  $45 \pm 5$  psia  
and  $38 \pm 0.4^\circ\text{R}$ .

FIGURE 58

GENERAL ELECTRIC BYPASS FLOWMETER

MODEL Z-809

LIQUID HYDROGEN CALIBRATION

3 APRIL 63

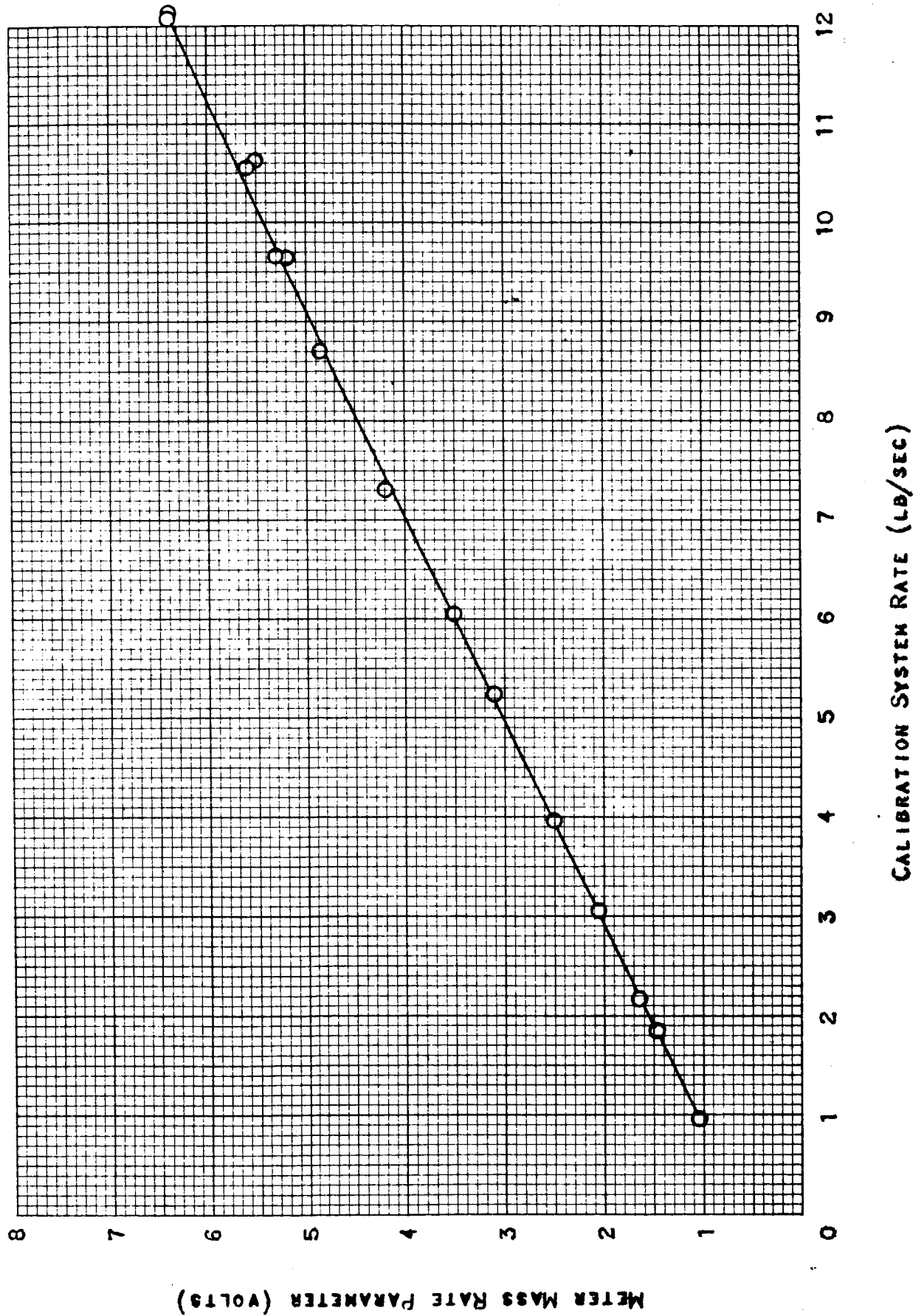


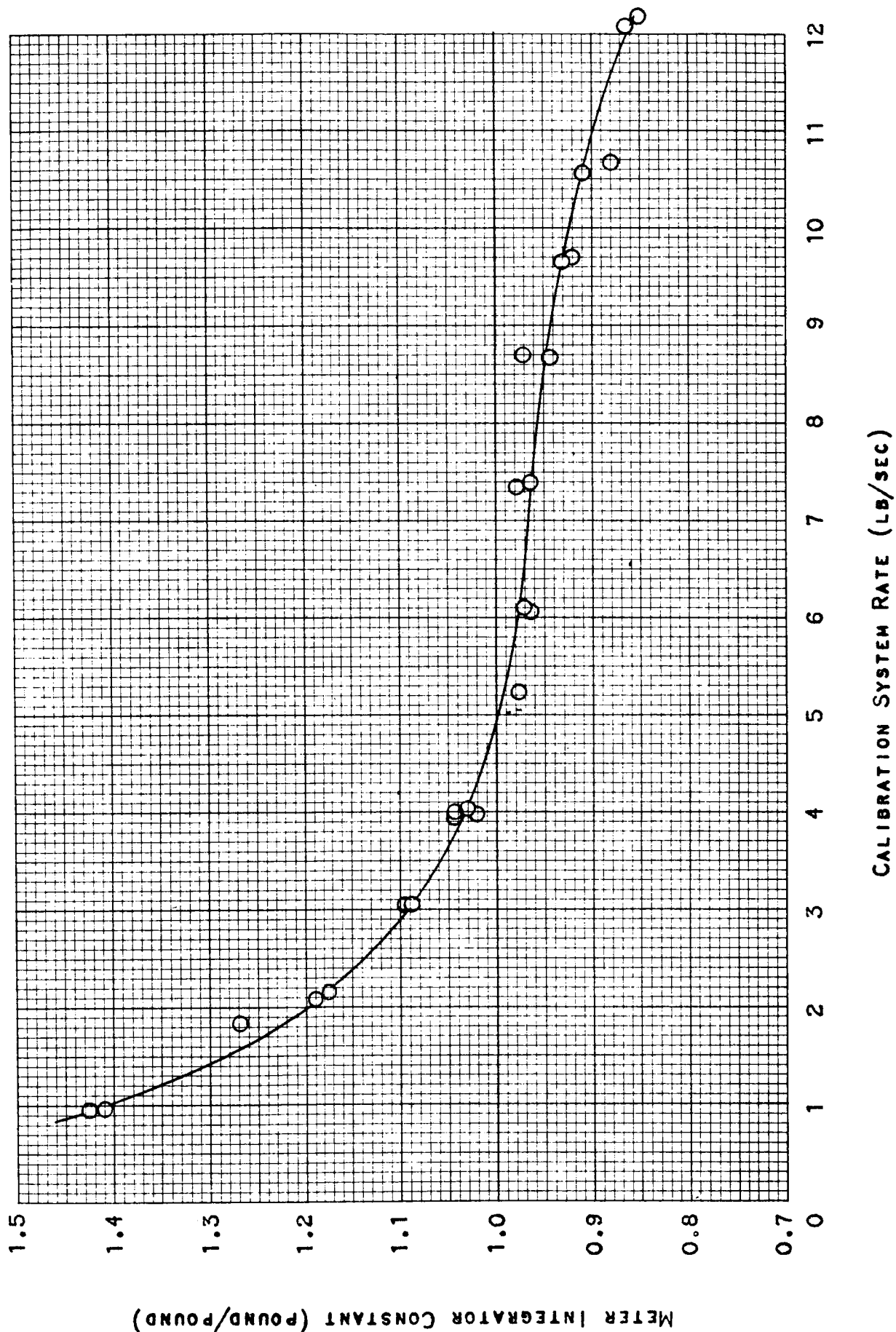
FIGURE 59

GENERAL ELECTRIC BYPASS FLOWMETER

MODEL Z-809

LIQUID HYDROGEN CALIBRATION

3 APRIL 63





GENERAL ELECTRIC BYPASS FLOWMETER

MODEL Z-809

LIQUID HYDROGEN PRESSURE DROP CHARACTERISTICS

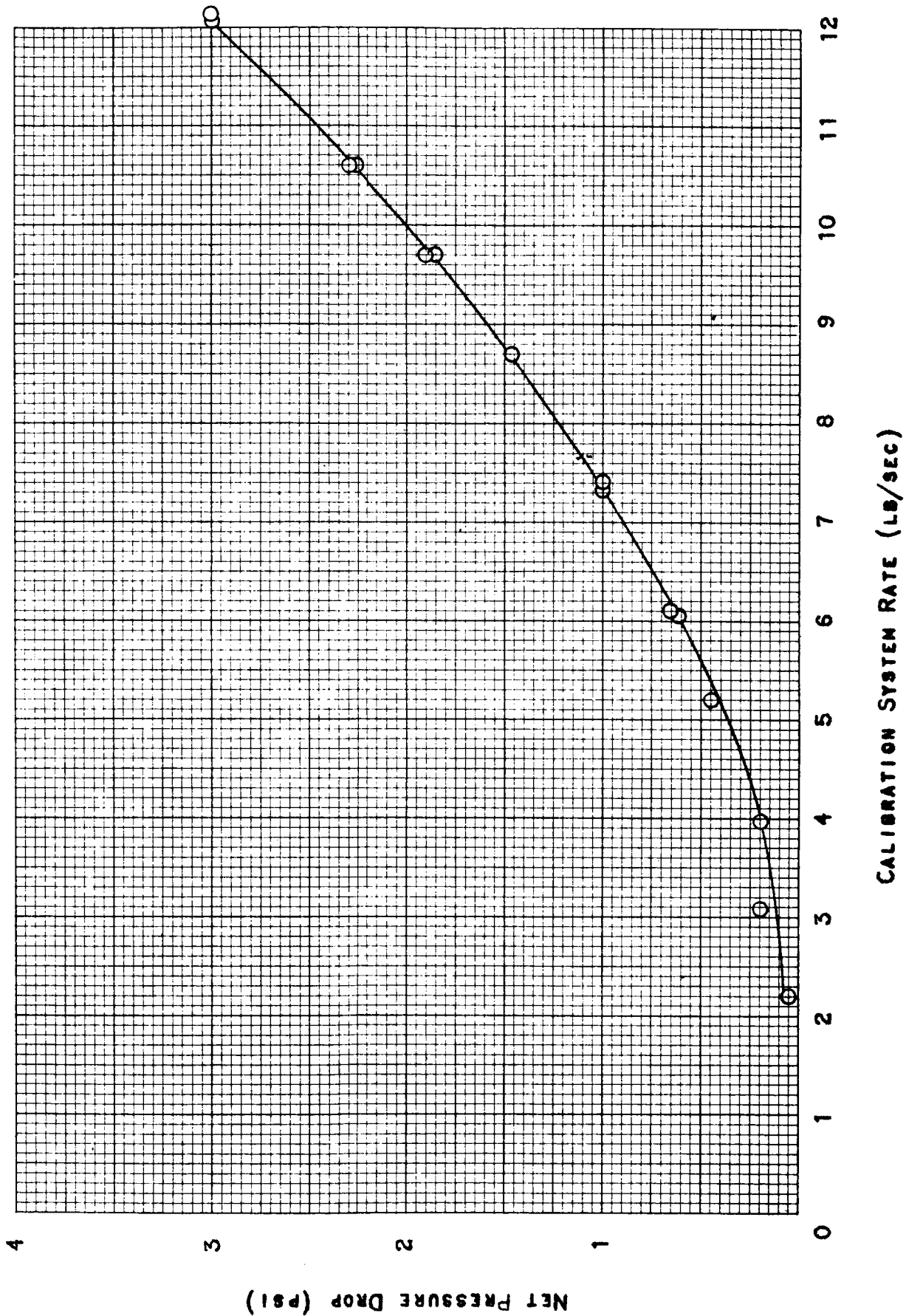


TABLE 25

GENERAL ELECTRIC BYPASS FLOWMETER  
MODEL Z-809  
LIQUID HYDROGEN-GASEOUS HELIUM DUAL PHASE CALIBRATION  
10 MAY 1963

Point No.	System Rate (lb/sec)	Gas to Liquid Ratio (% volume)	Integrator Output (lb)	Mass Rate Parameter (volts)
1	5.297	0	203.8	3.05
2	5.100	0	204.4	2.90
3	5.001	0	204.5	2.80
4	4.932	0	204.3	2.75
5	4.833	0	206.5	2.70
6	5.150	0	204.7	2.85
7	4.586	7.2	210.7	2.60
8	4.512	11.0	207.2	2.55
9	4.526	13.0	209.1	2.55
10	4.483	13.2	205.4	2.50
11	4.480	13.8	209.5	2.55
12	5.123	0	200.0	2.85

Note: Flowmeter inlet conditions were maintained at  $45 \pm 5$  psia  
and  $38 \pm 0.4^{\circ}\text{R}$ .

# GENERAL ELECTRIC BYPASS FLOWMETER

MODEL Z-809

## LIQUID HYDROGEN-GASEOUS HELIUM DUAL PHASE CALIBRATION

10 MAY 63

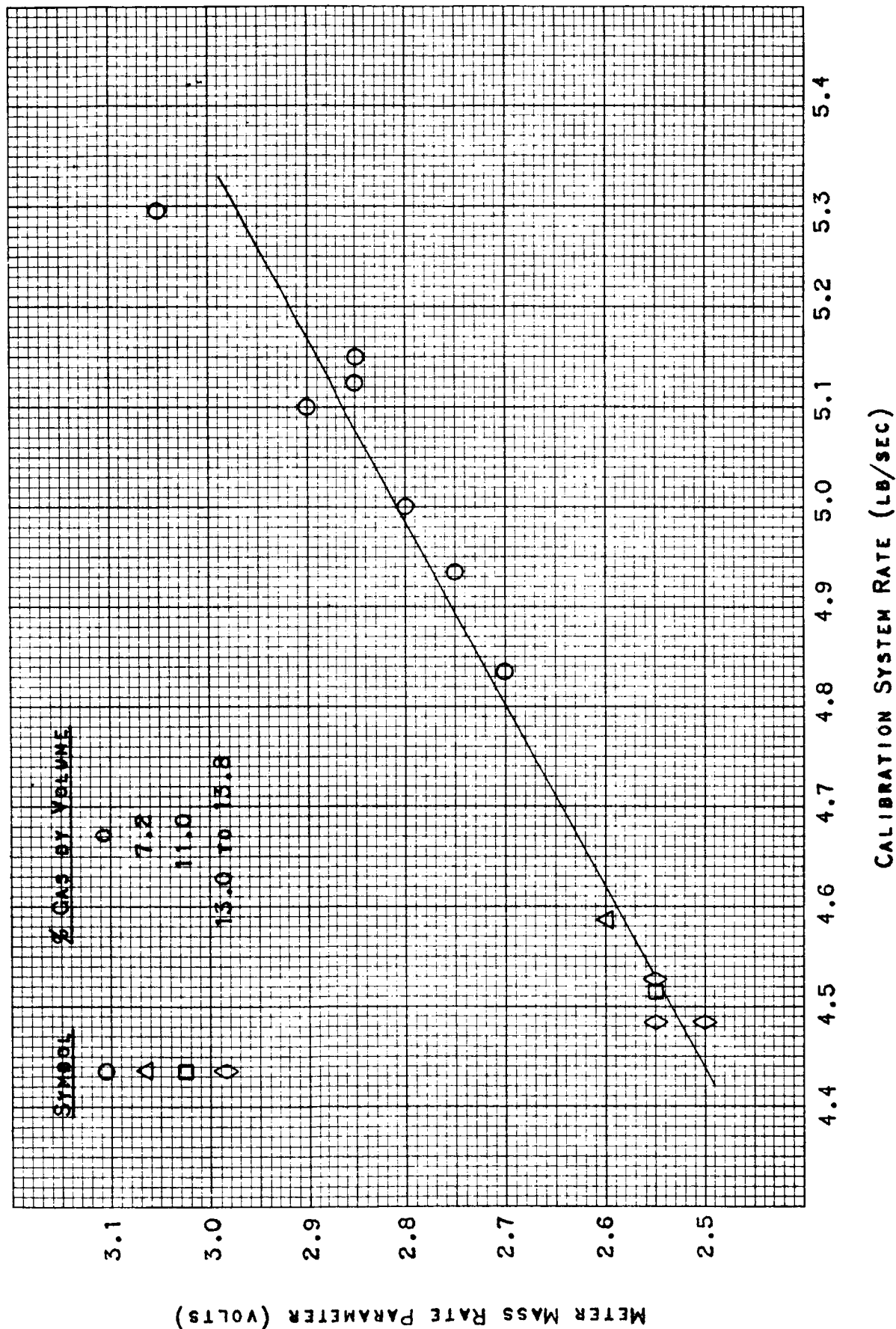


FIGURE 61

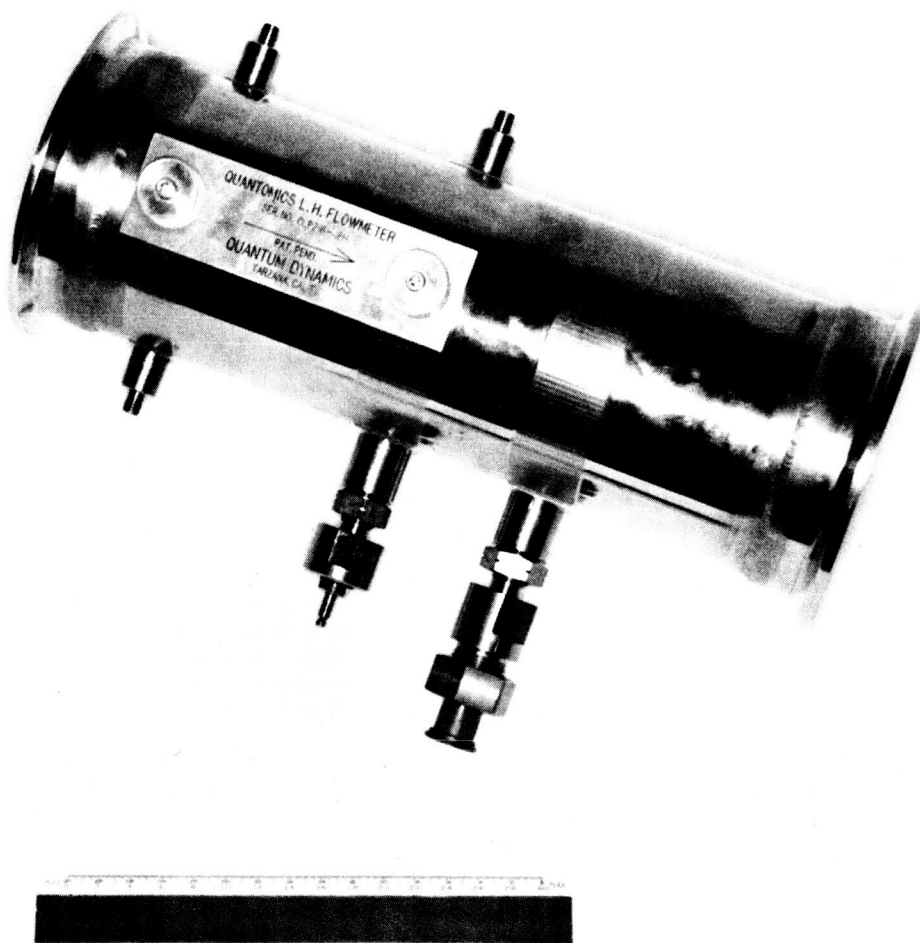
QUANTUM-DYNAMICS, COMPANY  
DENSITY COMPENSATING MASS FLOWMETER

Description

The Quantum-Dynamics mass flowmeter, shown in Figure 62, measures fluid density and volumetric flow rate independently, and combines these measurements electronically, arriving at a mass rate signal. The volumetric sensing element incorporates two design concepts not found in standard volumetric flowmeters. The first feature is that the volumetric turbine pickup utilizes a proximity-sensing method based on a high-frequency wave absorption principle to detect the rotational speed of the turbine, rather than the more conventional magnetic units. The advantage of utilizing this technique is that the magnetic loading on the turbine is eliminated. The second feature of the volumetric rate sensing system is the utilization of a slave turbine to reduce the relative velocity of the indicating turbine bearing assembly and, subsequently, the bearing drag. This is accomplished by installing the indicating turbine on the rotating shaft of the slave turbine.

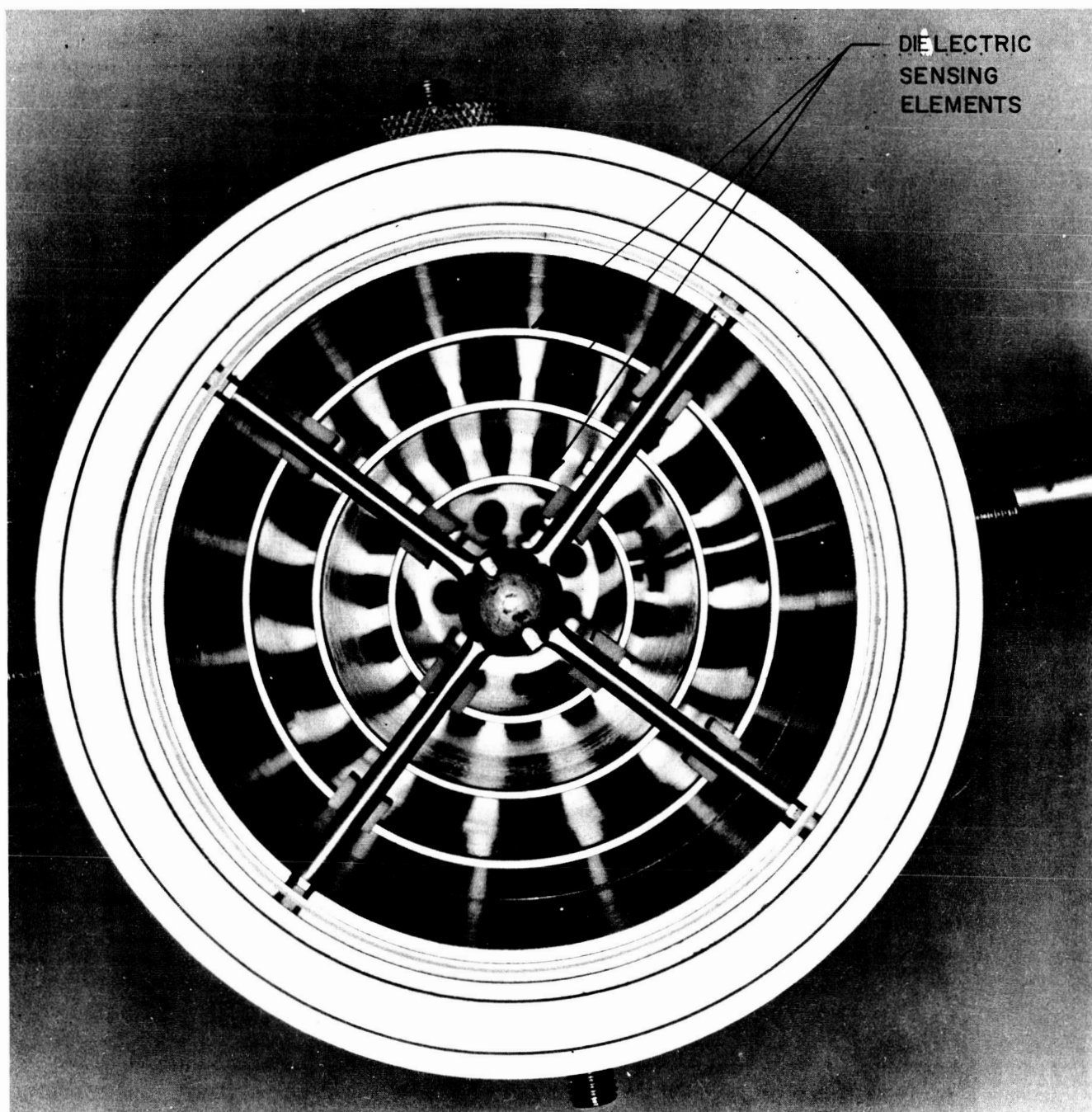
The fluid density sensing element consists of three concentric tubular sections, shown in Figure 63. The capacitance value of these concentric cylinders is a function of their specific geometry, and the dielectric constant of the fluid between them. The dielectric constant of liquid hydrogen and other cryogenic fluids has been shown to be a function of the fluid density. This relationship is defined by the Clausius-Mosetti equation, and is used as the basis for the design of the Dielectric to Density Converter, or D. D. C.

The signals from the dielectric sensing element and the velocity indicating turbine are fed to the D. D. C., a density proportional voltage is available for analog density requirements. The D. D. C. also supplies a signal to the PF/T Computer, which modifies the volumetric signal from the indicating turbine and generates a digital mass flow rate signal, a digital volume flow rate signal, and an analog volume flow rate signal. Figure 64 depicts this system schematically.



THE QUANTUM DYNAMICS, CO. 3-INCH MASS FLOWMETER

FIGURE 62



THE QUANTUM-DYNAMICS FLOWMETER INLET, SHOWING THE CONCENTRIC  
DIELECTRIC SENSING ELEMENTS

FIGURE 63

QUANTUM-DYNAMICS, CO.  
DENSITY COMPENSATING MASS FLOWMETER  
INSTRUMENTATION

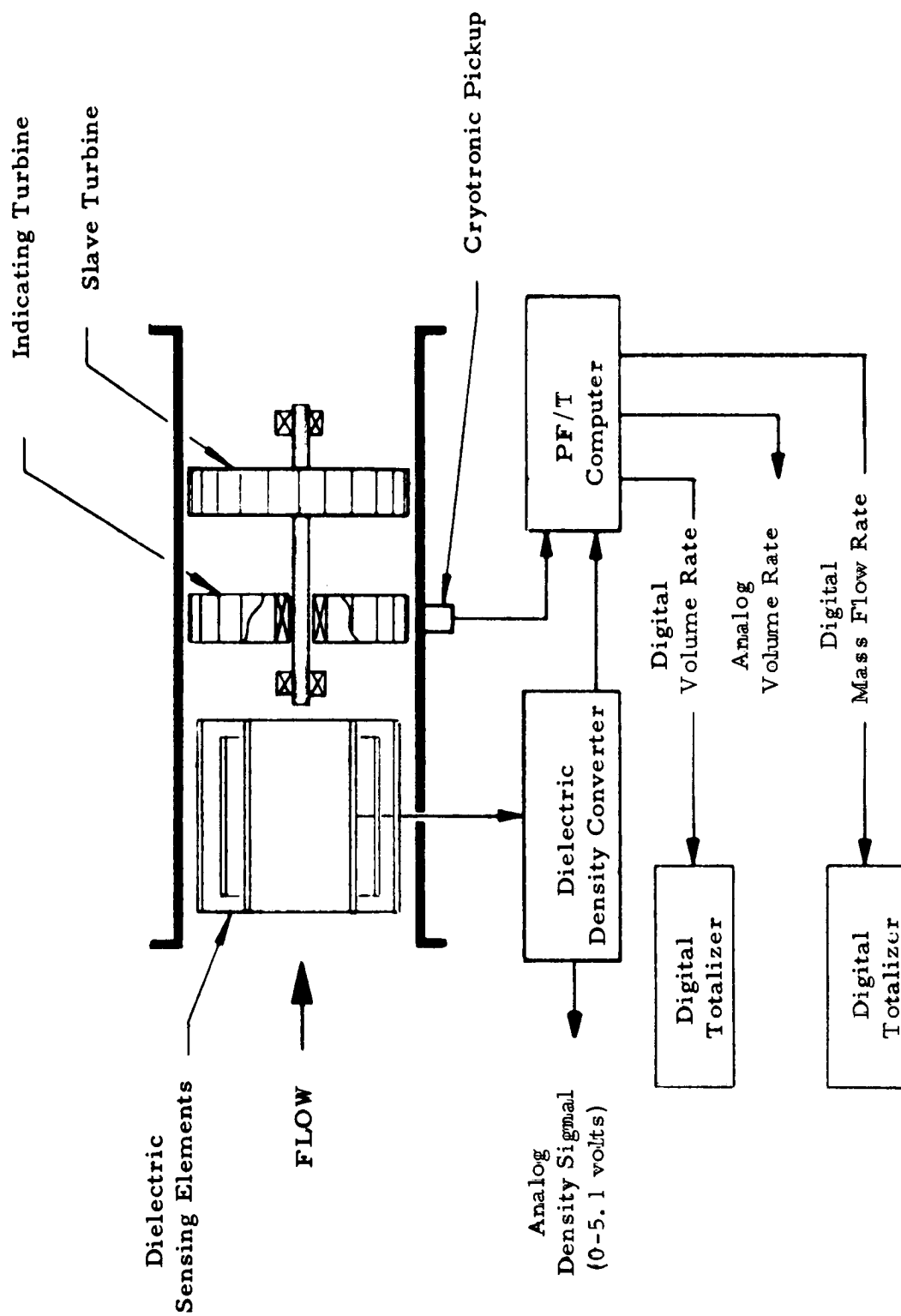


FIGURE 64

The advantages of the Quantum-Dynamics mass flowmeter system may be summarized as follows:

1. Independent density, volumetric and mass flow signals, simplifying the analysis of specific flow phenomena.
2. Provides both digital volume flow information and digital mass flow information.
3. Turbine design offers nominal pressure loss.

The Quantum-Dynamics mass flowmetering system possesses several characteristics which in some circumstances might be considered undesirable.

1. The turbine assembly may be subject to overspeeding during cooldown operations in cryogenic systems.
2. A relatively complex system of electronics is required to obtain the maximum data from the system.

#### Discussion of Test Data Obtained with the 3-Inch Quantum-Dynamics Flowmeter

The initial calibration work performed with the Quantum-Dynamics system was performed December 18, 1962, with flowmeter, Model QL-48-WRG-CT-E1. During these tests, several unanticipated problems arose which seriously limited the quantity of data obtained.

In installing the flowmeter in the calibration system, it was necessary to lengthen the leads between the flowmeter and the Dielectric to Density Converter. This modification upset the capacitance of the bridge circuit beyond its trimming limits. In addition, it was found that the ferrite core in the Cryotronic pickup was saturating, preventing the acquisition of flow data. The change in the performance characteristic of the ferrite core was found to be a function of temperature and was rectified prior to subsequent calibrations. As a result of the capacitance circuit problem no mass data was obtained, and the malfunctioning of the Cryotronic pickup resulted in the acquisition of only limited volumetric data. The volumetric data which was obtained, however, appeared extremely encouraging with a data spread of approximately  $\pm 0.1\%$  as shown in Table 26 and Figure 65.



TABLE 26

QUANTUM-DYNAMICS MASS FLOWMETER  
PART NUMBER QL-48-WRG-CT-E1  
LIQUID HYDROGEN CALIBRATION  
18 DECEMBER 1962

Point No.	System Rate (lb/sec)	Volumetric Constant (cycle/lb)	Backup Potter Flowmeter Constant (cycle/lb)
1	4.009	64.57	135.3
2	4.011	64.69	135.4
3	4.002	64.70	135.5
4	5.247	64.68	135.2
5	5.272	64.62	135.3
6	5.466	64.23	134.5
10	6.575	64.69	134.4
11	6.568	64.66	134.1
13	1.301	64.52	134.5
14	2.768	64.60	135.0

Note: Flowmeter inlet conditions were maintained at  $45 \pm 5$  psia. and  $38 \pm 0.5^{\circ}\text{R}$ .

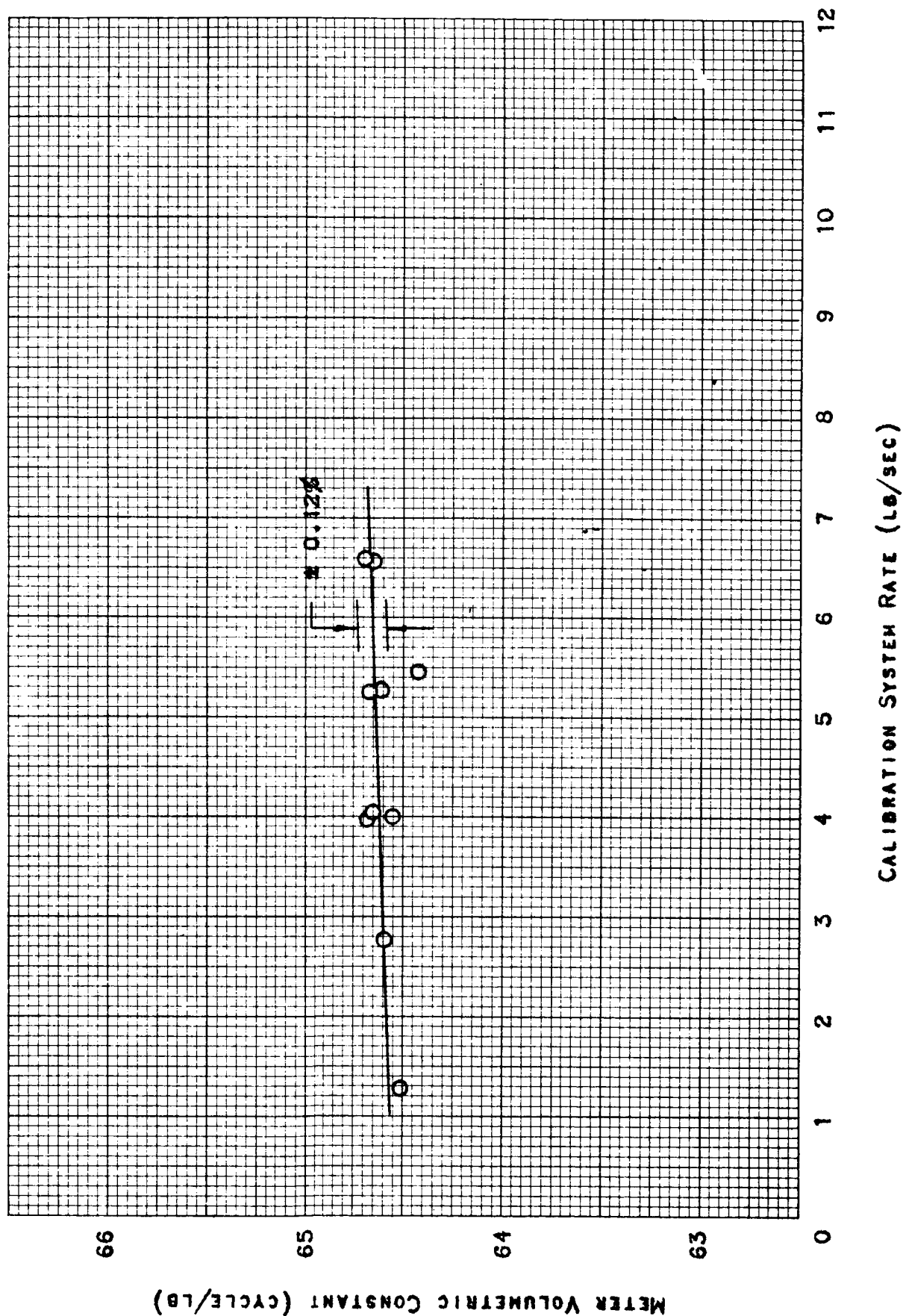
FIGURE 65

QUANTUM-DYNAMICS MASS FLOWMETER

PART NUMBER QL-48-WRG-CT-E1

LIQUID HYDROGEN CALIBRATION

18 DECEMBER 62



A second series of tests was conducted November 1, 1963, with flowmeter, Model No. OL-48-WRG-CT-E2. A number of minor modifications were incorporated in this unit which were determined necessary as a result of the initial tests on Model No. -E1. These modifications were:

1. The composition of the ferrite core in the cryotronic pickup was altered to provide more stability at cryogenic temperatures.
2. The connecting cable between the flowmeter's dielectric sensing element and the Dielectric to Density Converter was modified to facilitate installation in the test system.
3. A minor circuit error in the Dielectric to Density Converter which was noted during the tests of December 18 was corrected.
4. The balancing circuits in the Dielectric to Density Converter and PF/T Computer were modified to facilitate more rapid calibration and wider range of operation.

The data obtained during the calibration tests performed November 1, 1963 are presented in Table 27 and Figures 66 through 69. The initial six data points were utilized to adjust and balance the D. D. C. and PF/T Computer. These preliminary adjustments are clearly evident in Figures 68 and 69.

Following the system adjustments, an additional fourteen data points were conducted. A review of these data points indicates a malfunction in the flowmeter following run seventeen, which caused a gross inconsistency in the data. The volumetric output from the flowmeter became erratic, and the output from the D. D. C. began to shift significantly. This shift in the D. D. C. output during runs eighteen through twenty is clearly shown in Figure 69. A probable cause for the shift in the density signal is the sensitivity of the capacitance of the lead between the dielectric sensing element and the D. D. C. to physical or thermal changes.

During runs eight through sixteen, the performance of the metering system was relatively stable, and the data obtained represents a limited index of its performance.

The mass output of the system, shown in Figure 66, indicates a potential performance of better than  $\pm 0.5\%$ , however; this evaluation is based on extremely limited data and should be assessed accordingly.

The volumetric data, shown in Figure 67 does not exhibit the close tolerance evident in the data of December 18; however, the absolute performance of the new Cryotronic pickup has not been fully evaluated. Subsequent calibration tests conducted November 23, 1963, shown in Figure 70 indicate volumetric performance on the order of  $\pm 0.35\%$ .

The density proportional voltage output of the D. D. C. , shown in Figures 68 and 69, indicates a density variation of approximately  $\pm 1.0\%$ . Evaluating the pressure and temperature measurements from point to point, indicates a density variation of  $\pm 0.25\%$ ; however, the absolute accuracy of these measurements was not adequate to critically evaluate the density sensing portion of the system.

A modification of the conductor between the dielectric sensing element and the D. D. C. was performed and installed, and additional tests conducted November 23, 1963. During these tests no suitable mass data was obtained and it was the opinion of the cognizant Quantum Dynamics representative that a more sophisticated correction should be undertaken.

The pressure drop characteristics of the Quantum Dynamics mass flow-meter are shown in Figure 71.

TABLE 27

QUANTUM-DYNAMICS MASS FLOWMETER  
PART NUMBER QL-48-WRG-CT-E2  
LIQUID HYDROGEN CALIBRATION  
1 NOVEMBER 1963

Point No.	System Rate (lb/sec)	Mass Constant (lb/lb)	Volumetric Constant (cycle/cu. ft.)	Average Density Output (volts)
1	3.933	61.177	286.7	4.115
2	5.138	63.136	286.8	4.100
3	6.245	63.498	286.9	4.091
4	7.347	57.385	288.5	4.409
5	8.155	57.315	287.3	4.419
6	8.779	58.405	289.0	4.484
7	9.369	59.661	285.7	4.621
8	9.929	60.253	288.5	4.627
9	10.633	60.635	288.5	4.660
10	11.102	60.183	286.3	4.667
11	12.006	64.623	286.3	4.689
12	9.844	60.037	285.3	4.657
13	8.255	60.167	288.0	4.625
14	6.333	60.062	288.9	4.597
15	4.024	60.369	289.1	4.607
16	2.929	60.846	286.8	4.666
17	1.614	61.202	290.2	4.605
18	1.058	68.972	322.2	4.794
19	8.245	61.946	277.5	4.951
20	5.107	65.139	287.2	5.045

Note:

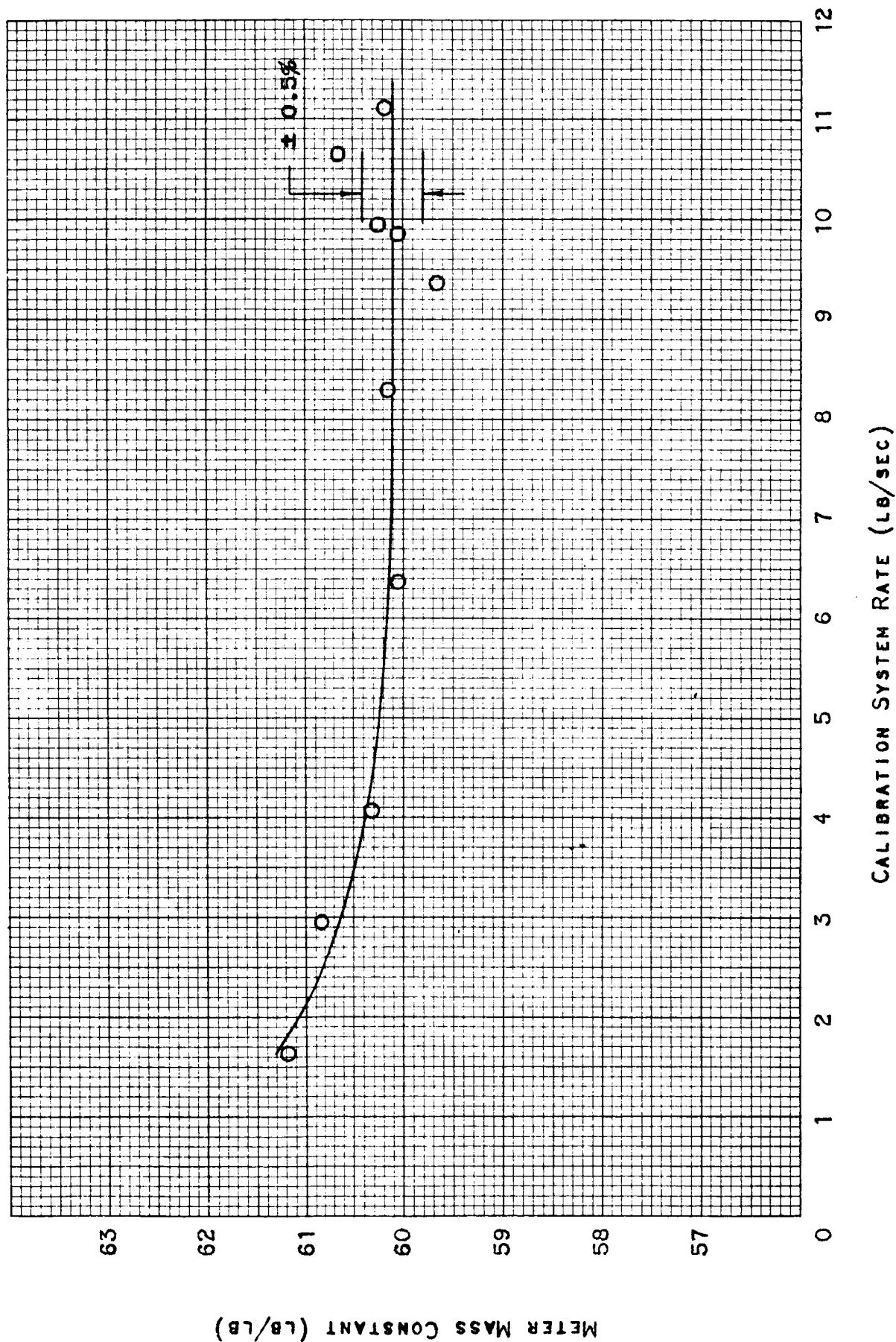
1. Electronic adjustments made during Point Nos. 1 through 6.
2. Point Nos. 18 through 20 discarded as invalid data
3. Flowmeter inlet conditions were maintained at  $45 \pm 5$  psia.  
and  $38 \pm 0.5^{\circ}\text{R}$ .

QUANTUM-DYNAMICS MASS FLOWMETER

PART NUMBER QL-48-WRG-CT-E2

LIQUID HYDROGEN CALIBRATION

1 NOVEMBER 63



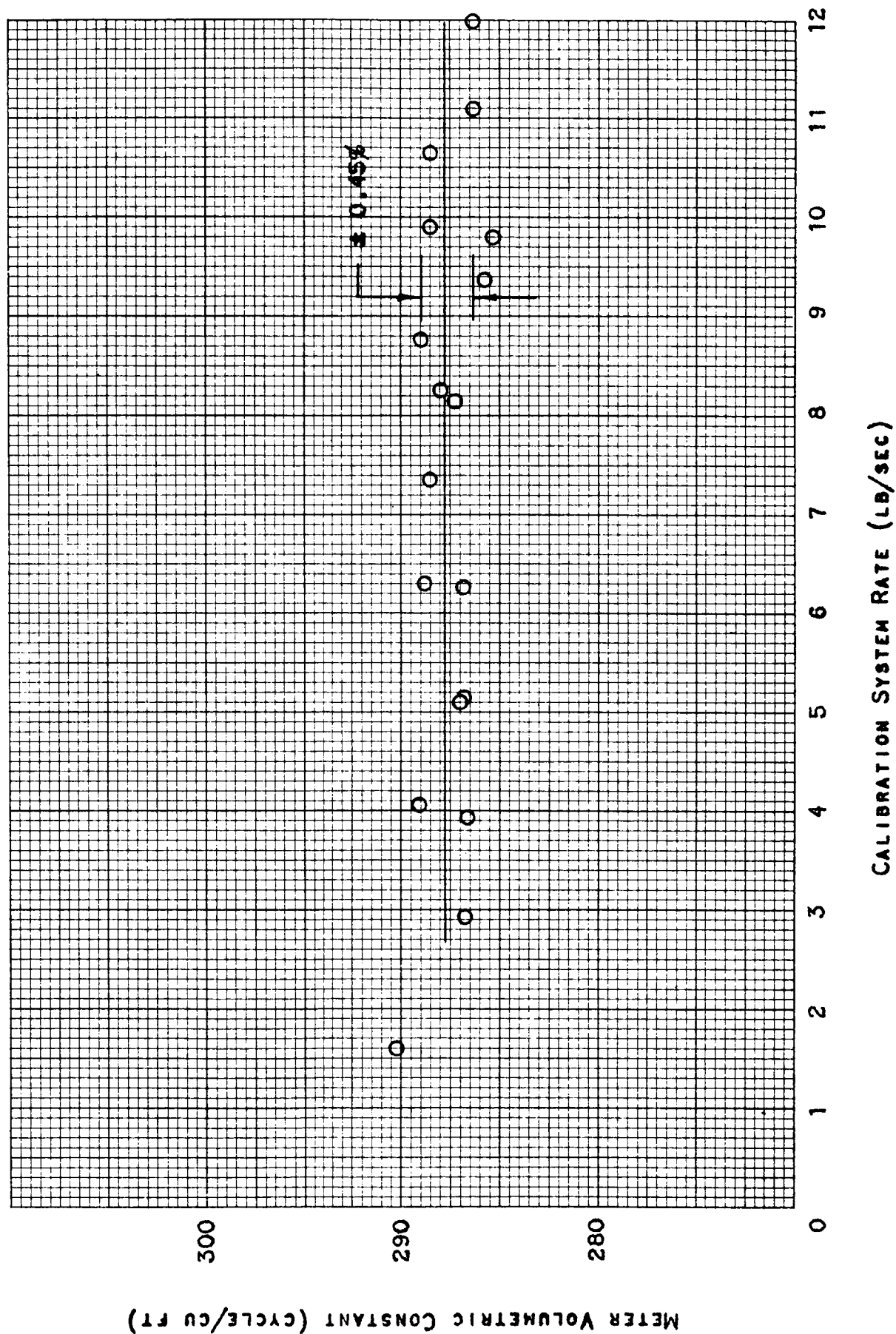
QUANTUM-DYNAMICS MASS FLOWMETER

PART NUMBER QL-48-WRG-CT-E2

LIQUID HYDROGEN CALIBRATION

1 NOVEMBER 63

FIGURE 67



QUANTUM-DYNAMICS MASS FLOWMETER

PART NUMBER QL-48-WRG-CT-E2

LIQUID HYDROGEN CALIBRATION

1 NOVEMBER 63

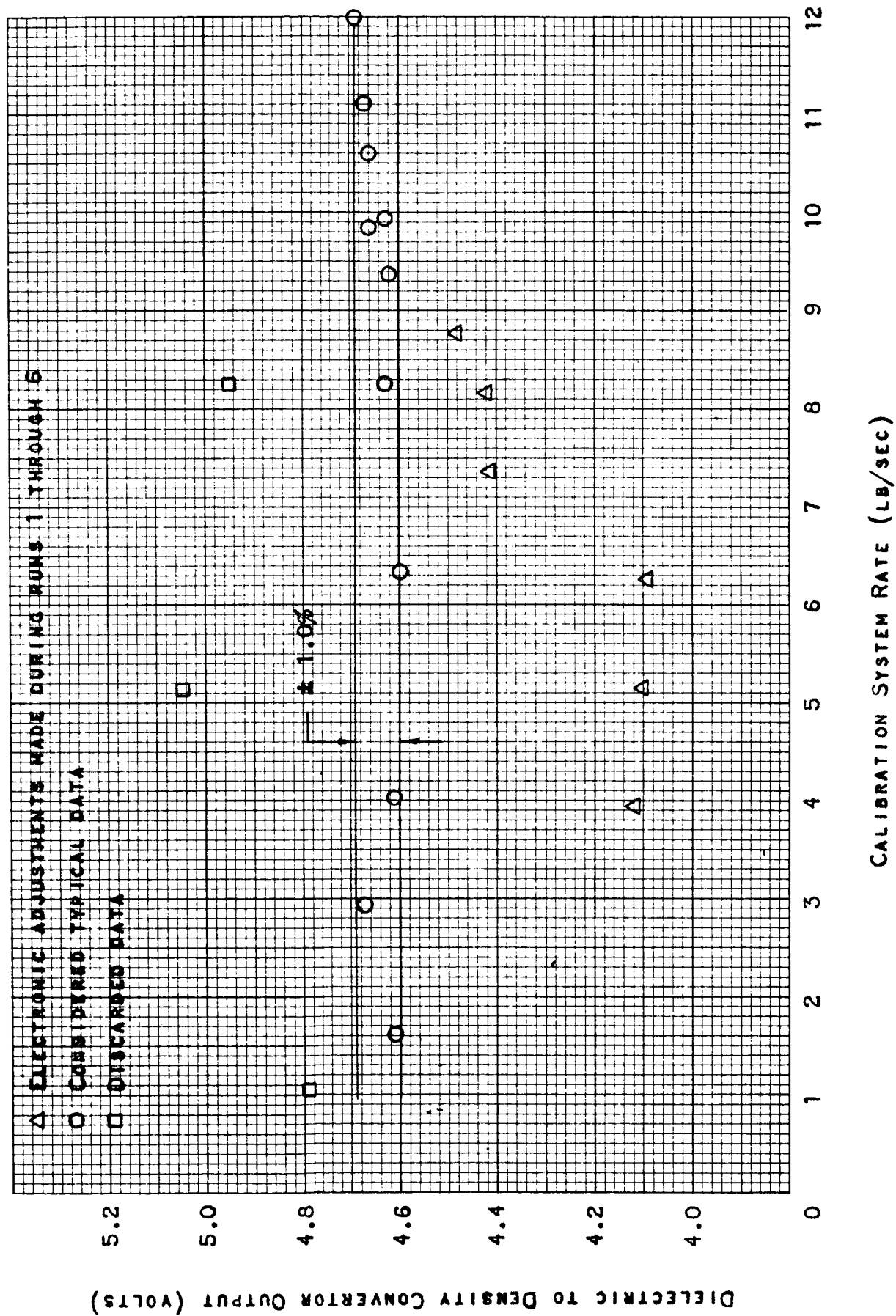


FIGURE 68



FIGURE 69

QUANTUM-DYNAMICS MASS FLOWMETER  
PART NUMBER QL-48-WRG-CT-E2  
LIQUID HYDROGEN CALIBRATION

1 NOVEMBER 63

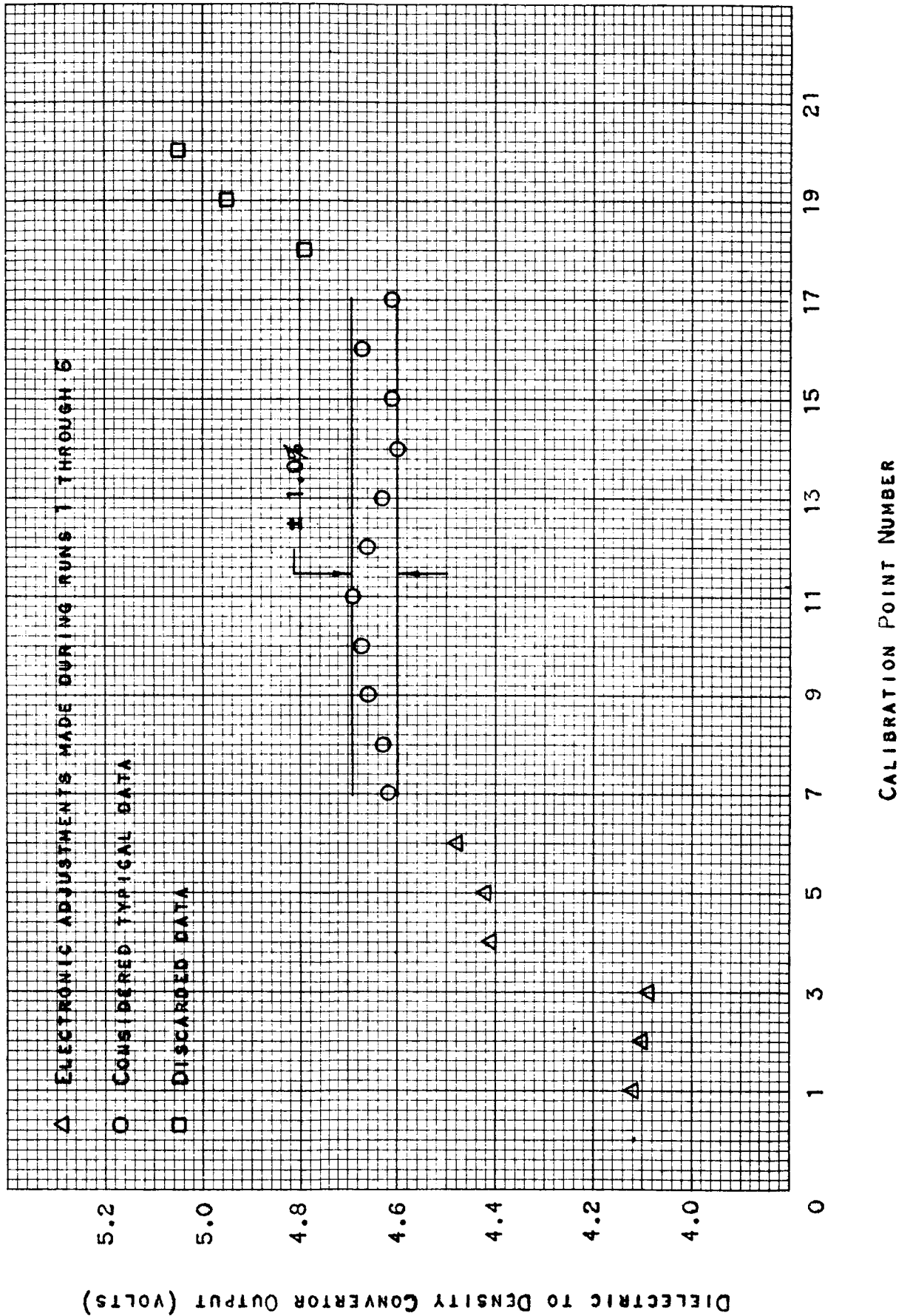


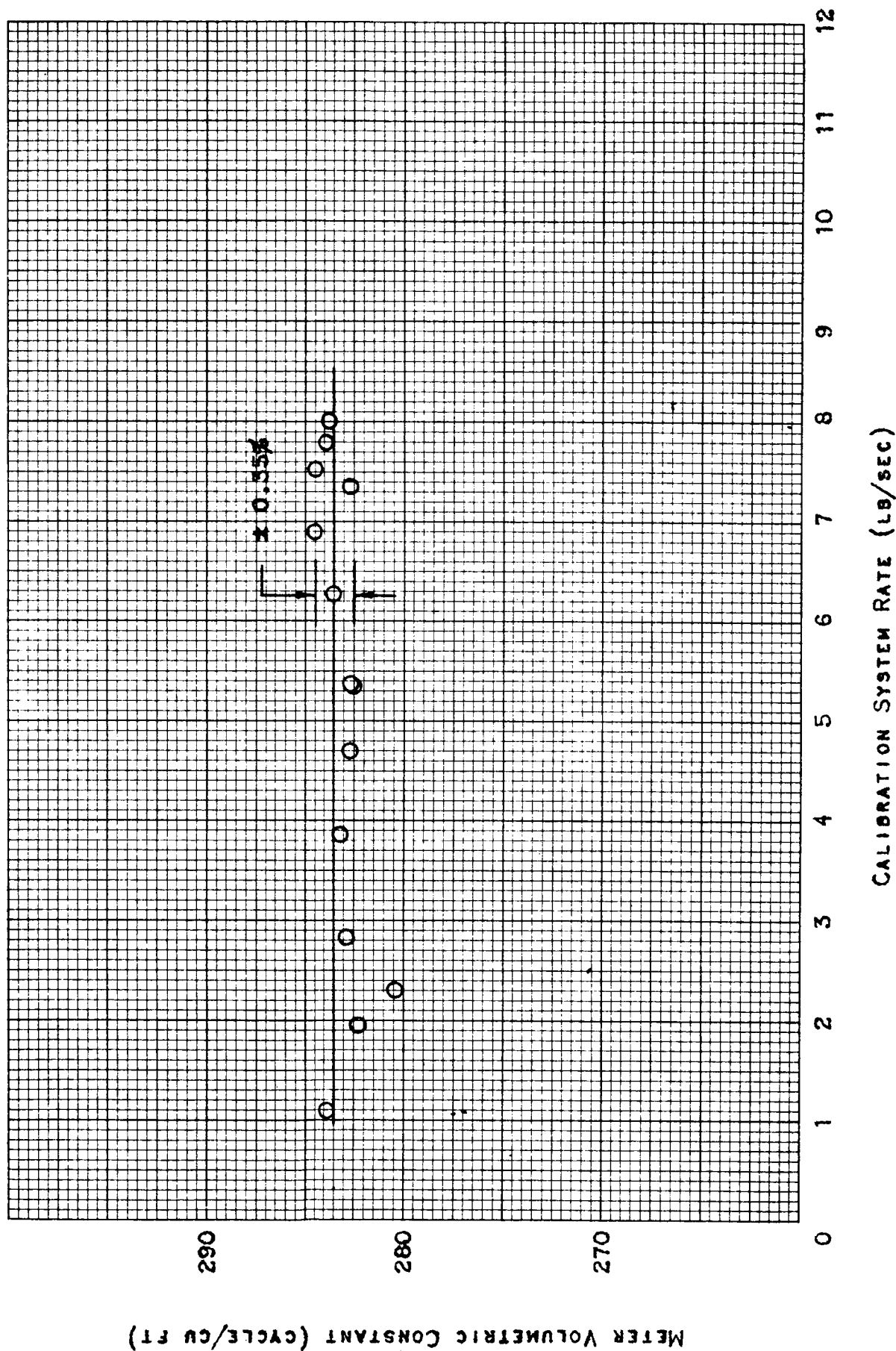
FIGURE 70

QUANTUM-DYNAMICS MASS FLOWMETER

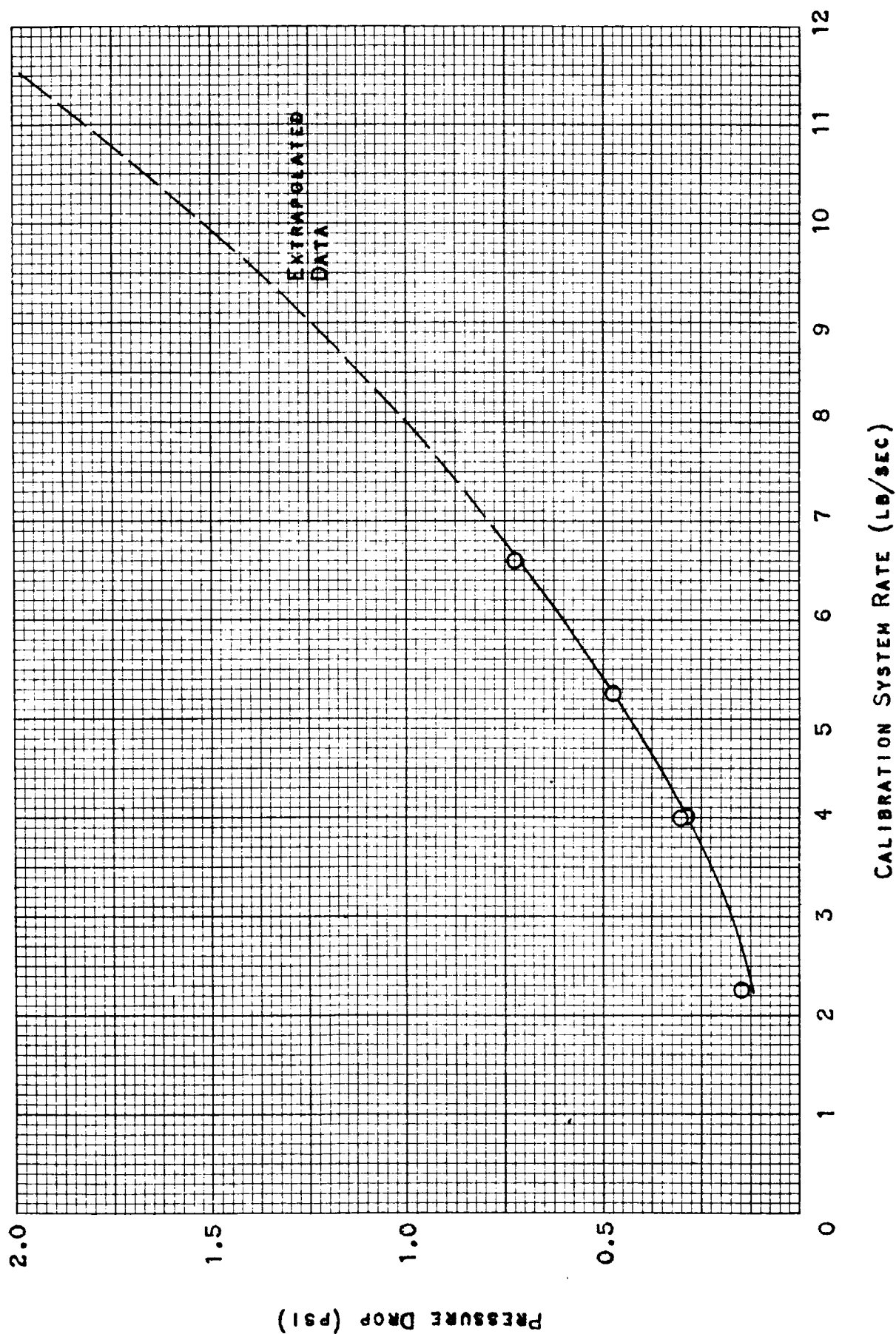
PART NUMBER QL-48-WRG-CT-E2

LIQUID HYDROGEN CALIBRATION

23 NOVEMBER 63



QUANTUM-DYNAMICS MASS FLOWMETER  
PART NUMBER QL-48-WRG-CI-E2  
LIQUID HYDROGEN PRESSURE DROP CHARACTERISTICS



## BIBLIOGRAPHY

1. Armour Research Foundation Report. "Study of Mass Flowmeters," ARF Project D173, Contract DA-11-022-ORD-2857.
2. Mortenson, L. N., "Design and Operation of a High Accuracy Calibration Stand for Cryogenic Flowmeters," Proceedings of the 1960 Cryogenic Engineering Conference, Boulder, Colorado, K. D. Timmerhaus.
3. Shafer, M. R. and Ruegg, F. W., "Liquid Flowmeter Calibration Techniques," ASME Paper Number 57-A-70, 1957.